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FIFTH QUARTERLY PROGRESS REPORT

LANDSAT FOLLOW-ON INVESTIGATION

NO. 21300

A. TITLE OF INVESTIGATION: LANDSAT Survey of Near-Shore Ice Conditions Along the Arctic Coast of Alaska

B. PRINCIPAL INVESTIGATOR: Dr. William J. Stringer

C. PROBLEMS IMPEDING INVESTIGATION: None

(E76-10428) LANDSAT SURVEY OF NEAR-SHORE ICE CONDITIONS ALONG THE ARCTIC COAST OF ALASKA Quarterly Progress Report (Alaska Univ., Fairbanks.) 53 p HC $4.50 CSCL 08L
N76-28604
Unclas
G3/43 00428

D. PROGRESS REPORT:

Using LANDSAT band 7 imagery at 1:500,000 scale, preliminary near-shore ice maps have been made for late spring and early summer 1973, 1974 and 1975. The maps are at present ready for proof-reading and annotation. With the completion of these maps, analyzing of three years' ice conditions will be complete and development of a morphology of near shore ice conditions can begin.

An ice reconnaissance of the Beaufort Sea was made and is reported here under Section E.

The paper presented last year at the conference on Port and Ocean Engineering Under Arctic Conditions was submitted for publication in the proceedings (copy attached as Appendix A).

A paper concerning Beaufort Sea ice conditions was prepared for presentation at the 31st Annual Petroleum Mechanical Engineering Conference, Mexico City, September 16, 1976.

INTERACTION WITH OTHER INVESTIGATORS AND AGENCIES:

The major result of interactive efforts was on aerial reconnaissance of the Beaufort Sea with Messrs. Dick Mortiz and Jeff Rogers of the Institute of Arctic and Alpine Research, Boulder, Colorado. The reconnaissance took place in mid-June between Barrow and Barter Island.

The main objective was to positively identify and locate major ice features for later correlation with features identified on LANDSAT imagery for the current year.

Another objective was color-infrared photography of melting ice conditions to answer questions arising from analysis of U-2 and simulated color IR LANDSAT imagery.

Some questions were answered regarding the tension crack phenomena discussed in earlier quarterly reports, under the "INTERACTION" heading: The cracks close in again after opening (perhaps weeks

21300

later) and in such a way that the ice thickness is even greater at the former crack location. For this reason, it appears unlikely that seals maintain breathing holes along the cracks after they open.

This last winter an oil company attempted to build a temporary exploratory island in Harrison Bay. The island was constructed by pumping sea water onto the desired location and allowing it to freeze. The project had been abandoned because of scheduling difficulties. The recurring Thetis Island crack discussed earlier passed within a mile of the uncompleted structure.

F. PLANS FOR NEXT REPORTING PERIOD:

(1) Near shore ice maps will be completed.
(2) Correlation of meteorological data with ice conditions will begin.

G. RECOMMENDATIONS: None

H. FUNDS EXPENDED: As of May 30, 1976, the total funds expended were $10,048.

I. DATA USE:

Value of Data Allowed	Value of Data Ordered	Value of Data Received as of 6/30/76
$14,500	Standing Order	$11,578

J. PUBLICATIONS:

See Appendices A and B.

K. SIGNIFICANT RESULTS:

See attached sheet.

L. APPENDICES:

Appendices A and B are attached.

FIFTH QUARTERLY PROGRESS REPORT

LANDSAT FOLLOW-ON INVESTIGATION

NO. 21330

TITLE: LANDSAT Survey of Near-Shore Ice Conditions Along the Arctic Coast of Alaska

PRINCIPAL INVESTIGATOR: William J. Stringer

DISCIPLINE: Oceanography

SUBDISCIPLINE: Ice Dynamics

SUMMARY OF SIGNIFICANT RESULTS: None this reporting period.

APPENDIX A.

Ice Motion in the Vicinity of a Grounded Floeberg.

Presented at the Third Conference on Port and Ocean Engineering under Arctic Conditions, Fairbanks, Alaska, August 1975. Appendix A is in preprint form as submitted for the proceedings.

ICE MOTION IN THE VICINITY OF A GROUNDED FLOEBERG

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ABSTRACT

The grounded ice feature at 162°W, 72°N, known as "Katie's Floeberg" provides ice researchers with a versatile tool for measuring many parameters related to the physical and morphological characteristics of sea ice. This paper considers the effect of the grounded ice feature on ice motion and relies almost entirely on data obtained from the Landsat and NOAA II satellites. Because of convergence of meridians at the earth's poles, it is possible for Landsat to image the floeberg up to three days in succession making possible sequential Landsat observations under somewhat constant wind and ice conditions.

The influence of the floeberg on ice motion can be considered at three scales: 1) local (tens of km) where significant alteration of ice motion and structure can take place; 2) meso-scale (hundreds of km) where alteration of ice structure is limited and modification of ice motion consists chiefly of introduction or modification of shear; 3) large scale (thousands of km) where the relationship of the floeberg to ice motion may be merely a small perturbation on an already existing pattern.

Local scale ice motion analysis yielded information related to the motion of pack ice past the obstruction. Ice appears to be subject to considerable breakage while passing the feature. However, the "breaking zone" is confined to the area within two well-defined boundaries.

Meso-scale analysis shows that on the occasions when a well-defined "breaking zone" exists, a "shear zone" does not take place. Rather, shear takes place along the distinct boundaries of the "breaking zone".

The magnitude of influence on large scale ice motions by the floeberg is very likely that of a perturbation and is somewhat difficult to gauge because of the fortuitous location of the feature. However, on at least one occasion it appeared to act as a cutting edge between ice driven into the Chukchi Sea (toward the Bering Straits) and ice driven along the north coast of Siberia (motion of the Pacific Gyre).

INTRODUCTION

In recent years there has been an increasing interest in the behavior of Arctic Ocean ice and in particular its interaction with shoreline features, islands, and other stationary objects in near-shore areas. Chief among the reasons for this interest are the constraints placed on petroleum extraction-related activities by the behavior of arctic ice. While just a few short years ago the mechanics and morphology of ice in Arctic waters were the domain of study of only a handful of arctic scientists, these topics now hold great interest for many industrial engineers. Numerous experiments are being carried out to better determine stress-strain laws, the crushing strength, and other properties of sea ice related to the placement of structures in arctic waters.

Besides these experiments designed to measure specific properties of sea ice, natural ice phenomena are under observation to test the relationship of these properties to the gross morphological behavior of arctic ice under natural conditions. Chief among these natural ice phenomena sought for observation is the behavior of ice forced to move past an obstruction. Obviously this would simulate conditions imposed on a drilling platform or artificial island. Along Alaska's arctic coast there are many islands which could serve as locations for these observations except the ice flows parallel to them only a very short time before the creation of a belt of stable "shore-fast" ice along the coast. After that time the islands are hidden behind this belt of ice. Further, this activity takes place during the darkest winter months when observation is difficult.

This paper concerns a naturally-occurring ice feature which acts as an obstruction to ice motion and is located sufficiently far from the coast that it is always surrounded by ice that is free to move. Landsat imagery is used to document the effect of this obstruction on the surrounding ice pack. These results are then applied to the problem of man-made structures located within moving ice.

LARGE ICE FEATURES IN THE ARTIC OCEAN

Ice Islands

By far, the vast majority of ice in the North American sector of the Arctic Ocean is frozen sea water. Icebergs in the usual sense are unknown, although it is possible that fragements of icebergs may occasionally be found. However, there are rather large ice features - sometimes more than 30 meters thick and up to 10 km in horizontal dimension - called "ice islands". These large tabular blocks of ice have rather conclusively been related the Ellesmere Ice Sheet in the Canadian Arctic. There is good evidence that as the ice sheet slides off Ellesmere Island, ice islands are broken off and eventually drift away to join the Arctic pack ice. Because of summer ablation, these ice islands decrease in thickness at a rate of up to 30 cm per year, depending on location. Hence, an ice island remaining in the Arctic Ocean can be expected to last many years.

Floebergs

Although considerably smaller, another species of large ice features found in the Arctic Ocean are floebergs. The World Meterological Organization defines floeberg as: "A massive piece of sea ice composed of a hummock, or a group of hummocks, frozen together and separated from any ice surroundings. It may float up to 5 m above sea level". Floebergs can be several "melt seasons" old. In this case, the voids in the original hummock have been filled with ice, resulting in a much strengthened structure.

KATIE'S FLOEBERG

For several years, the Navy sea ice reconnanissance teams have occasionally made note of ice features (which they designated "floebergs") located on seamounts located in the Chukchi Sea west of Barrow, Alaska. One of these seamounts is located at 70°30'N, 171°30'W and the other at 72°N, 162°W. At this later location the Navy has noted a persistent feature since 1972. About that time Lt. Commander William Dehn made a special trip to that location to verify conclusions he had drawn based on analysis of low resolution weather satellite imagery. He had observed a persistent polynya at the seamount location and had surmised that a stranded floeberg was the cause.

Quite independently of the Navy discovery, the feature was brought to our attention by Mrs. Katherine (Katie) Martz, the University of Alaska Remote Sensing data librarian. We have since referred to it as "Katie's Floeberg". As part of the University's Remote Sensing program, she had been requested to watch out for unusual ice features in the off-shore Landsat data received. Of particular interest at that time was the identification of ice islands on satellite data and a determination of their frequency of occurrence. During the spring of 1974, Mrs. Martz brought the feature at 72°N, 162°W to our attention saying that it didn't appear to be an ice island because it had been at that location the previous year also. Upon inspection of the two years' data it was evident that the feature had moved very little if at all. Examination of the Landsat imagery also strongly indicated that the pack ice was being driven around the feature.

A few months after our "discovery" of the feature, we were provided with a flight to its location by the Naval Arctic Research Laboratory at Barrow. This flight took place on July 11, 1974. By that time, the pack was moderately well broken up, and there was considerable open water. At that time, the feature had the appearance of old, weathered, multi-year hummocked ice. In many of the Landsat images examined there had been a polynya extending from the southwest end of the feature. At the time of our inspection, this end appeared to have the greatest freeboard (~ 5 m) and the most solid appearance. There were no large, flat areas anywhere, although some ice was quite well-rounded.

Upon our return to Barrow we discussed the feature with Mr. James Cotant, a member of the Navy Sea Ice Reconnaissance team, who informed us of the Navy's awareness of this feature. The Navy referred to the feature as a "grounded floeberg".

INFLUENCE OF KATIE'S FLOEBERG ON ICE MOTION

The existence of the floeberg makes possible observations of the interaction of a single, isolated obstruction with the pack ice. Although man-made islands are being constructed to act as drilling platforms, very little information exists which will allow prediction of the results of the interaction of these structures with moving pack ice. Examination of the Landsat data available showed that the interaction between the floeberg and the pack ice could be considered in terms of three scales:
1) local (within 20-30 km); 2) Meso-scale (within 150 km); and 3) Long range (1000 or more km).

For these analyses it was necessary to have time-lapse data. Fortunately because of the overlap of Landsat's polar orbits at high latitudes, it is theoretically possible for the floeberg to be imaged three or four days in succession. At least two images will include sufficient overlap to allow a detailed examination of the interactions. Landsat coverage is such that this opportunity is repeated every eighteen days. Hence it is theoretically possible to study ice motions on the order of days as well as weeks.

During spring, 1974, two pairs of images were obtained eighteen days apart. These dates were March 20 and 21 and April 7 and 8. Much of the analysis presented here is based on these data.

Meso-scale Ice Motions

Cursory examination of Landsat imagery reveals ice motions at this scale: That is, the motions can easily be seen on sequential pairs of standard 1:1,000,000 scale Landsat images. Observations of ice motions at local scale requires examination of enlarged images while long range influences on ice motions can only be observed by means of large field of view satellite data.

Ice motions over 24-hour periods

i. March 20/21, 1974. Figures 1 and 2 show Landsat scenes containing Katie's floeberg on March 20 and 21, 1974. The March 20 image shows the floeberg located to the north of an adjacent polynya (at this latitude Landsat images are oriented top to bottom in a nearly northeast-southwest direction). The March 21 image (whose center point is located to the west of the center point of the March 20 image) shows the floeberg located approximately eastward of an adjacent polynya. It is not obvious from examination of these images just what relative displacements have taken place and whether or not they are uniform across the image. It can be seen that several SE-NW oriented leads have opened around the floeberg to the southwest.

Figure 3 shows the floeberg surrounded by the vector displacements of nearby ice during the 24-hour period between the acquisition of these two images. The first impression given by this figure is that displacements vary in a somewhat systematic way, increasing from north to south. Actually, the displacements fall into two groups. The first contains 35 vectors and extends from the northeast to the floebergs, and the second, containing 25 vectors, extends from the floeberg to the bottom (southwest) part of the figure. The velocity corresponding to the upper group is 6.5 cm/sec with an average deviation of 0.3 cm/sec while the velocity of the lower group is 8.7 cm/sec with an average deviation of 0.6 cm/sec. These larger velocities correspond to the ice broken off by the NW-SE trending lead systems.

It is interesting to compare the ice motion during this time with isobars or simultaneous weather charts. Figures 4 and 5 show reproduced portions of Canadian Enviromental Service surface charts with arrows near the location of the floeberg (location circled) indicating the direction of ice motion, which is nearly parallel to the isobars. Actually, one would expect surface winds to deviate from the geostrophic approximation, having an additional southward component resulting from surface friction and a consequent diminished Coriolis acceleration. However, because of Coriolis acceleration of the ice which has been set in motion by the wind, there will be a component of the drift forces toward the right of the instantaneous direction of motion. Zubov (1944) pointed out that these two factors generally compensate for one another with the result that pack ice generally drifts along isobars as appears to be the case here.

ii. April 7/8, 1974. Figures 6 and 7 show Landsat images of the floeberg and vicinity for April 7 and 8, 1974. Sky conditions were not entirely clear at this time: some rather thin clouds cast a number of shadows across the image. However, not all ice details are obscured. Examination of the April 7 image shows the floeberg on the left-hand side of the image surrounded by fragmented pack ice and a re-frozen polynya adjacent to the southwest side. Apparently, major motion had ceased for a time sufficient for the polynya to freeze up to the floeberg. However, adjacent to the floeberg there is a fresh lead approximately one kilometer wide indicating that ice motion toward the southwest had recently been initiated.

Figure 1. Landsat I image showing "Katie's Floeberg" on 20 March 1974, at 1:1,000,000 scale.

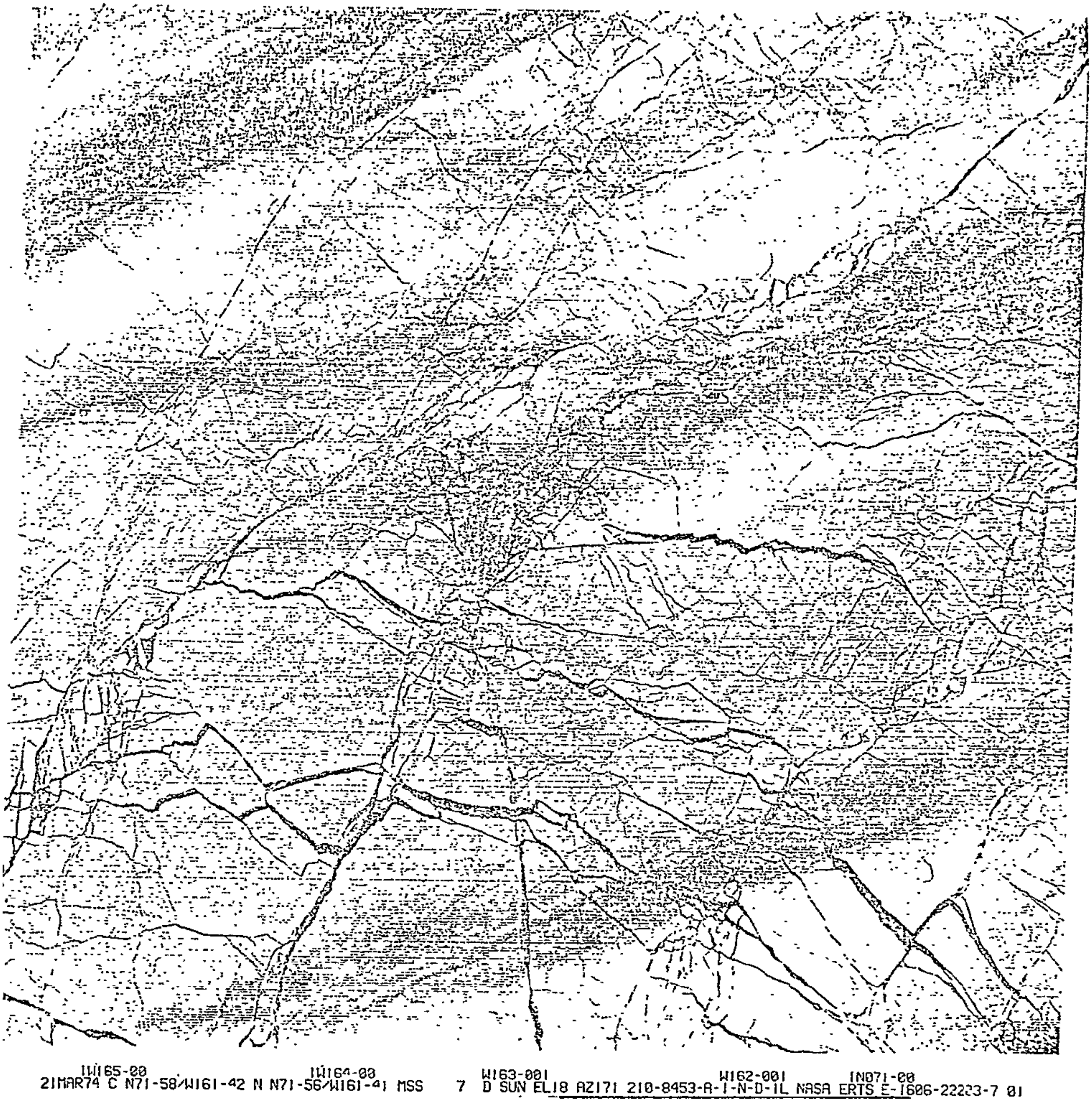

Figure 2. Landsat I image showing "Katie's Floeberg" on 21 March 1974, at 1:1,000,000 scale.

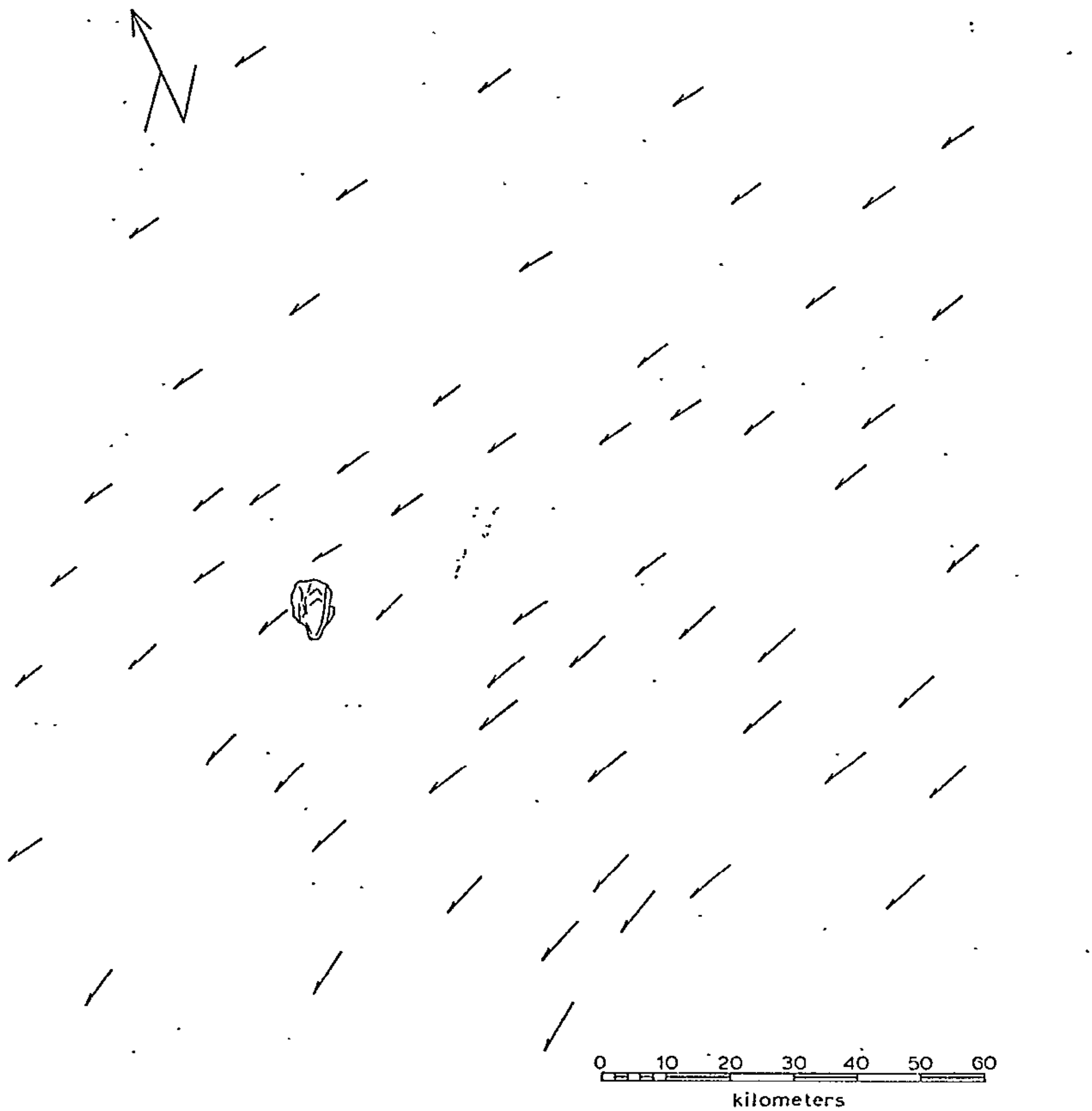

Figure 3. Diagram showing ice flow vectors in the vicinity of "Katie's Floeberg" for the period 22:14:50 UT, 20 March 1974, to 22:20:30 UT, 21 March 1974.

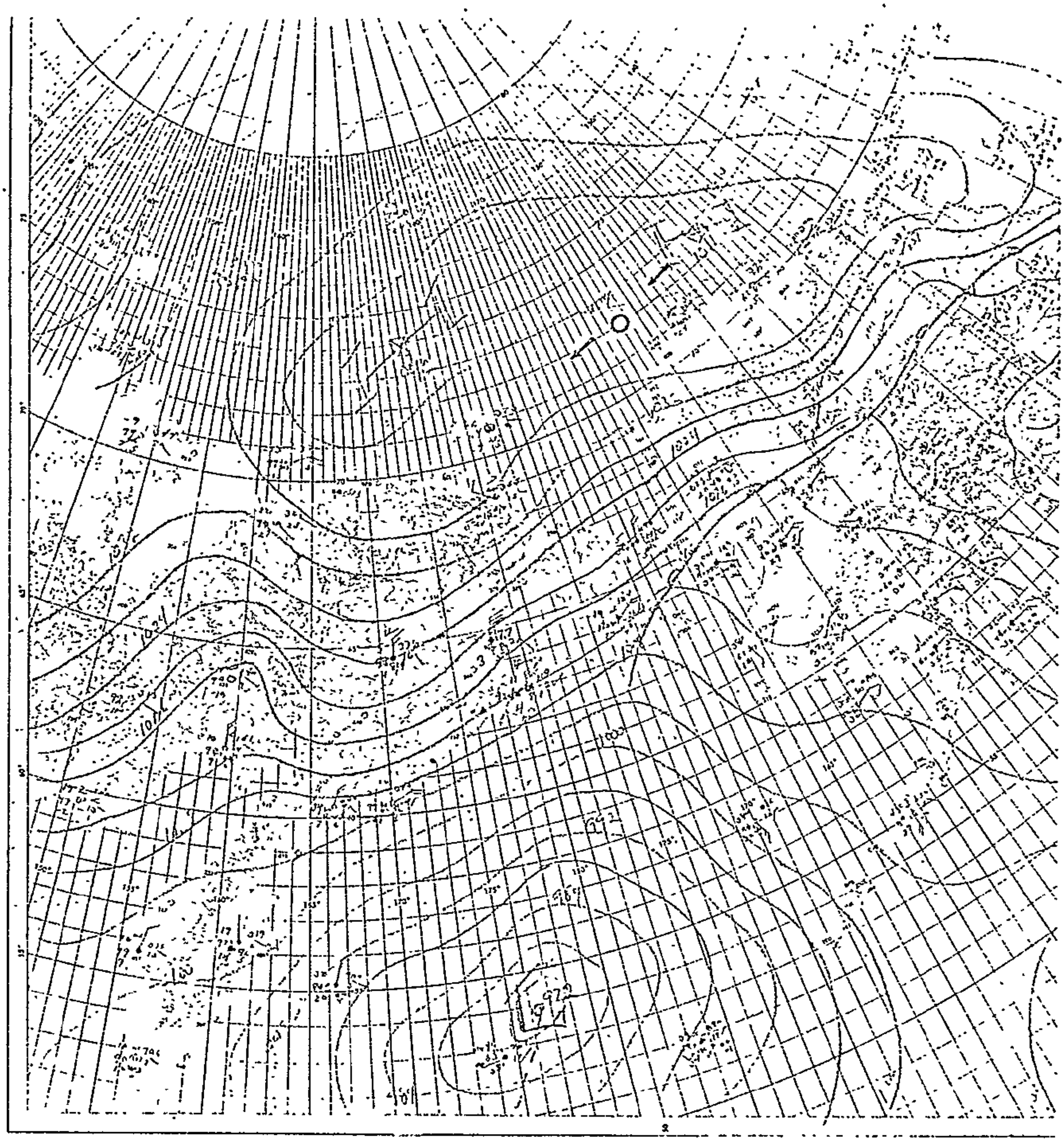

Figure 4. Canadian Environmental Services surface weather chart for 0000 hrs UT 21 March 1974 showing the location of "Katie's Floeberg" (heavy circle) and the observed direction of ice movement (arrows).

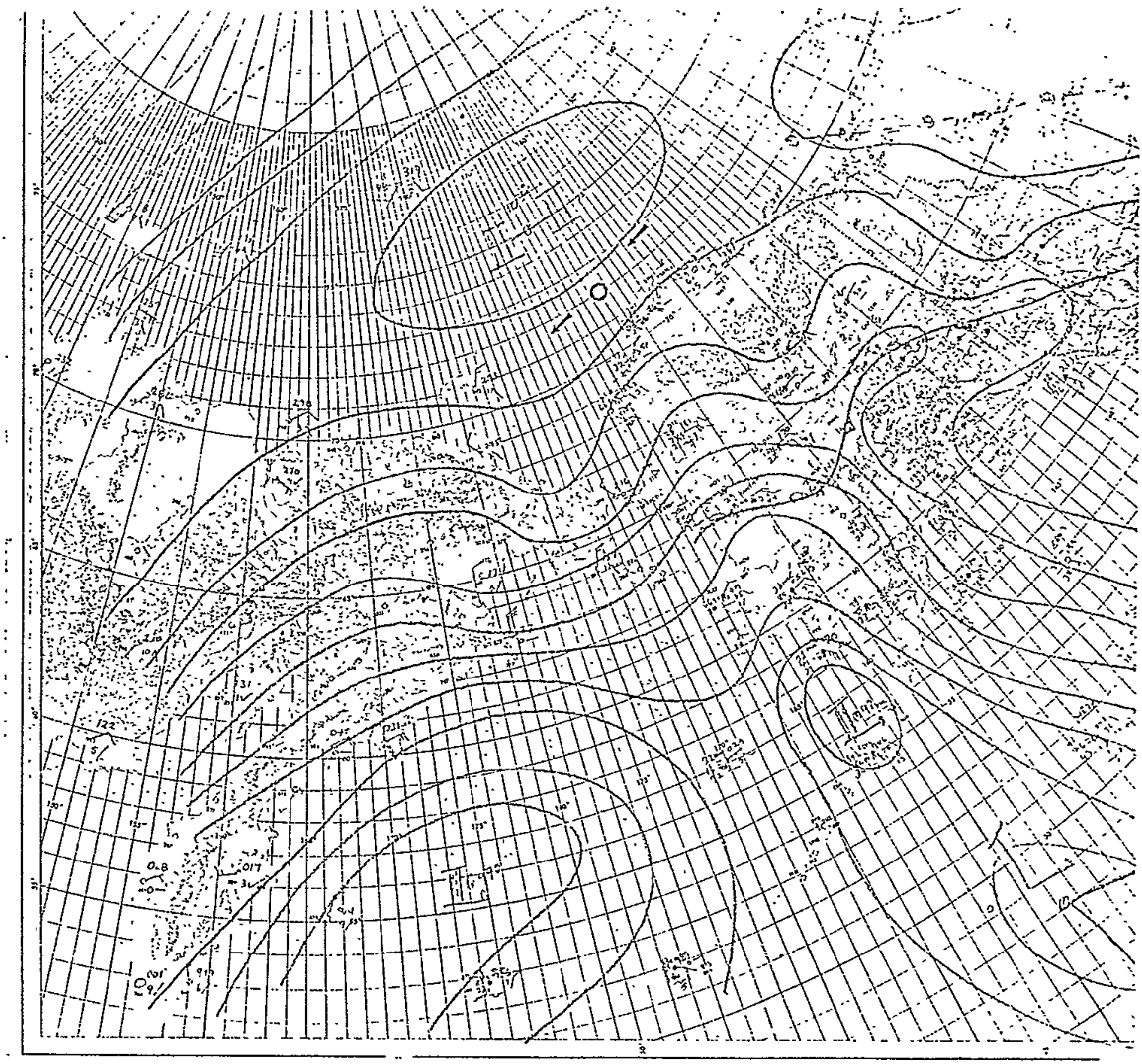

Figure 5. Canadian Environmental Services surface weather chart for 0000 hrs UT on 22 March 1974, showing the location of "Katie's Floeberg" and the observed direction of ice movement.

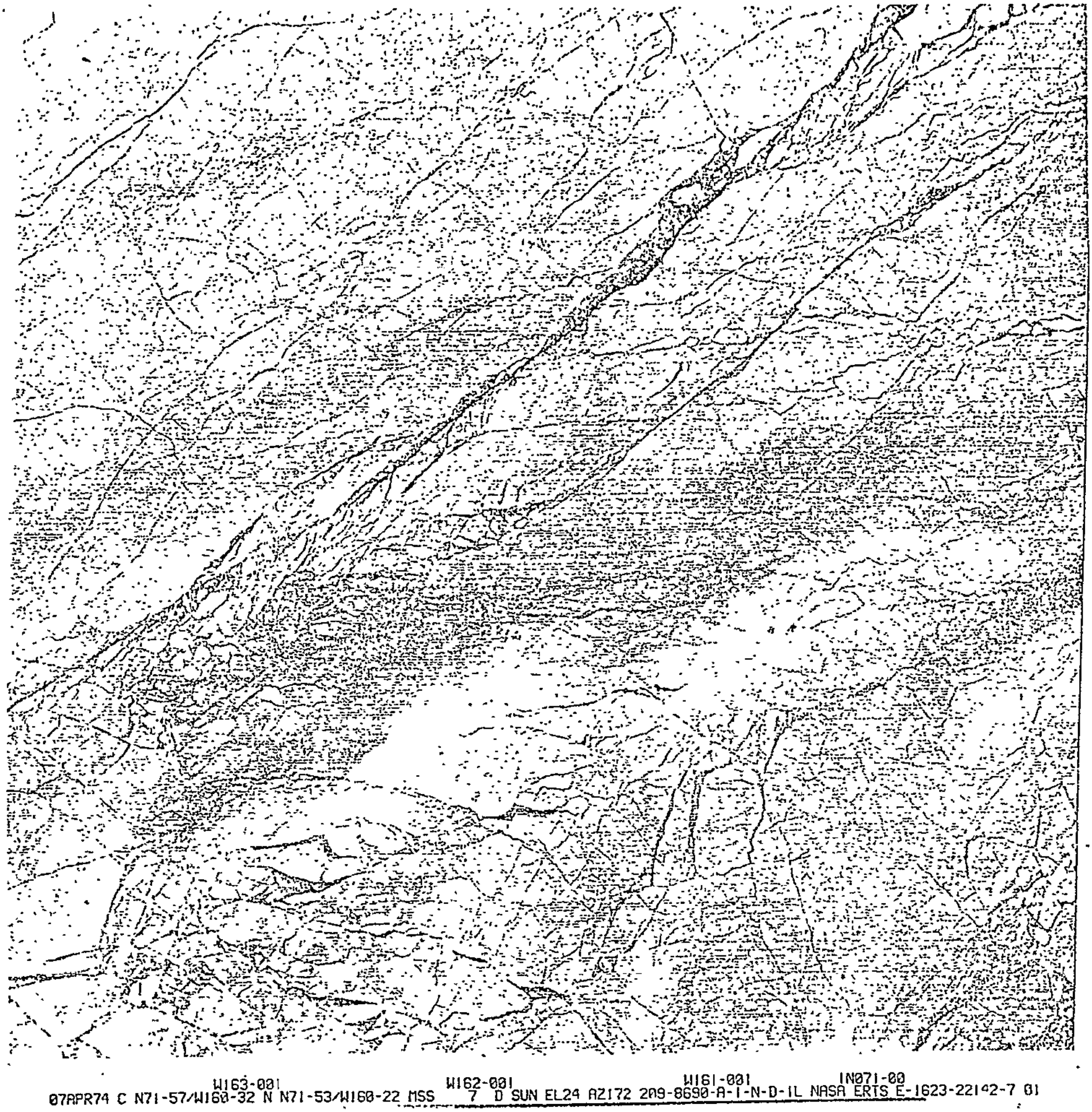

Figure 6. Landsat I image showing "Katie's Floeberg" on 7 April 1974 at 1:1,000,000 scale.

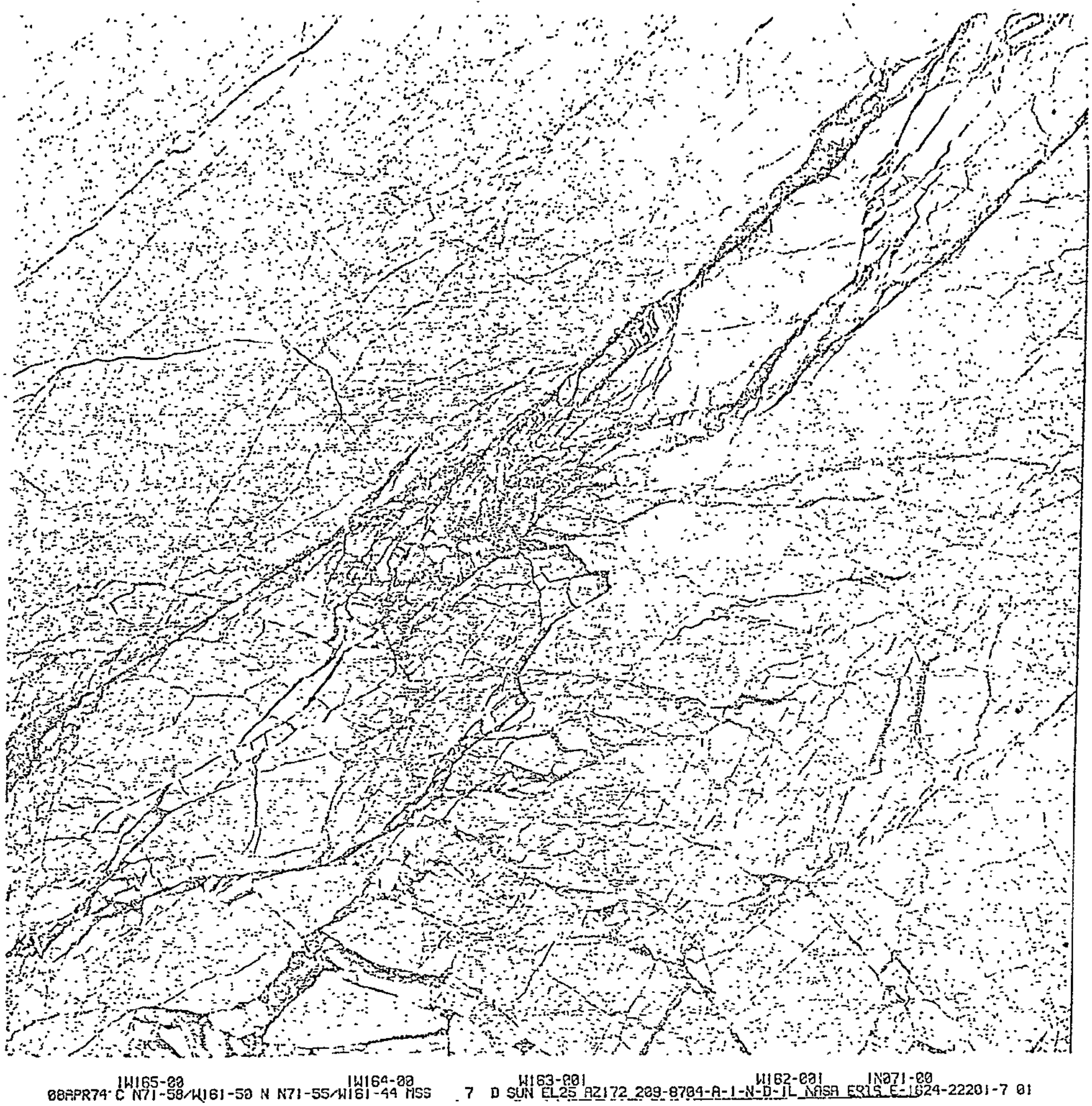

Figure 7. Landsat I image showing "Katie's Floeberg" on 8 April 1974 at 1:1,000,000 scale.

It is interesting to note the large east-west oriented lead running across the image just north of the floeberg. There is another lead, somewhat less conspicuous but parallel to this lead passing just south of the floeberg.

The April 8 image shows more distinct lead systems than the April 7 image. Further, it is clear that the ice adjacent to the floeberg has been in motion since the April 7 image: a large polynya has been formed to the west of the floeberg. It is still possible to see the impression left by the floeberg in the ice which had formed adjacent to the floeberg prior to this motion.

Figure 8 shows the floeberg surrounded by the vector displacements of nearby ice during the 24-hour period between the acquisition of the April 7 and 8 images. The displacements fall into five groups as shown in the following table:

Table of Velocities for April 7 - 8, 1974

Group	Location/Description	Average Velocity	Average Deviation
I	Pack ice north of floeberg	17.8 cm/sec	0.7 cm/sec
II	Slower moving ice just downstream	8 cm/sec	0.2 cm/sec
III	Slower moving ice just upstream of floeberg	9.6 cm/sec	0.5 cm/sec
IV	Block of vectors in lower left	6 cm/sec	0.4 cm/sec
V	Pack ice south of floeberg	3.9 cm/sec	0.5 cm/sec

The ice in Group I is located on the north side of the shear boundary just north of the floeberg. Referring to Figures 6 and 7 it can be seen that they represent a relatively continuous sheet of pack ice moving as one piece. Group V is the large block of vectors lying on the south side of the floeberg. It can be seen from Figures 6 and 7 that these represent an area of relatively broken-up pack ice with several freshly frozen-over leads.

Groups I and V are essentially part of the large scale picture and will be considered in detail in that section. However, some mention of the large scale picture of ice motions must be made at this point: Figure 9 shows an enlarged portion of a NOAA II image obtained at nearly the same time that Figure 7 was imaged by Landsat. The area covered by this image is approximately 1000 km east-west by 800 km north-south. The floeberg can be seen to the west of Point Barrow. Examination of this figure should verify that the ice in areas I and V is actually part of the large scale ice motion pattern and that the significantly slower speeds measured for motion of ice located between these two groups is essentially a result of the blockage of the large scale motion by the floeberg.

Groups II, III and IV represent ice apparently influenced by the presence of the floeberg and will be considered here in terms of meso-scale influences on ice motions.

The major group, Group III is roughly 15 km wide just upstream of the floeberg and necks down to a width of 8 km at the floeberg. It appears that the lower speed of this ice is a result of blockage of its motion by the floeberg. The mechanics of the blockage will be considered in the section on local-scale ice motions.

Finally, we consider the ice in Group IV. These vectors represent motions of individual pieces of ice which are part of a large block located "down stream" of the floeberg During the 24-hour period observed here, this block broke loose from block V and moved at a speed intermediate between blocks II and V.

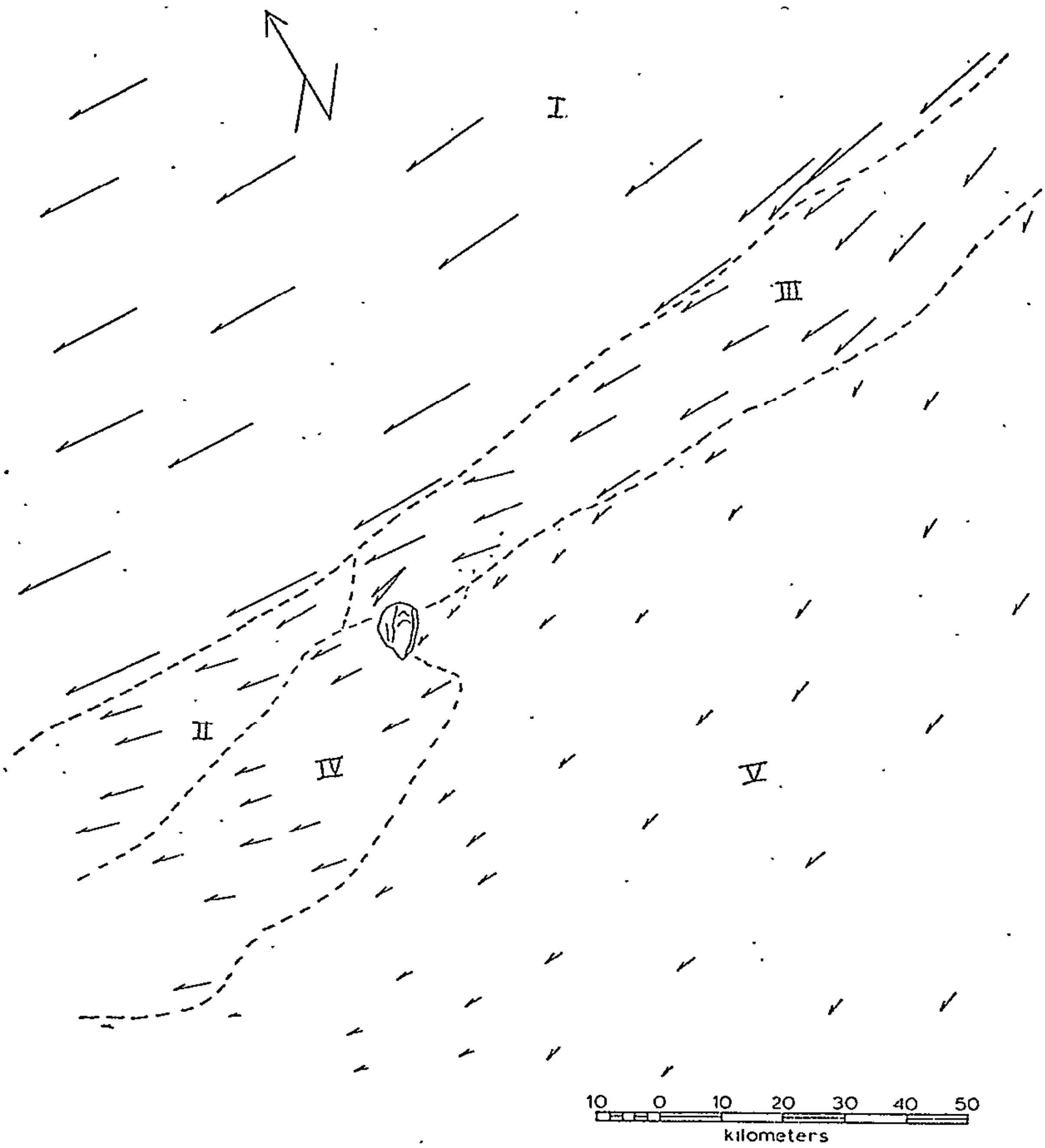

Figure 8. Diagram showing ice flow vectors in the vicinity of "Katie's Floeberg: for the period 22:14:20 UT, 7 April 1974 to 22:20:10 UT, 8 April 1974.

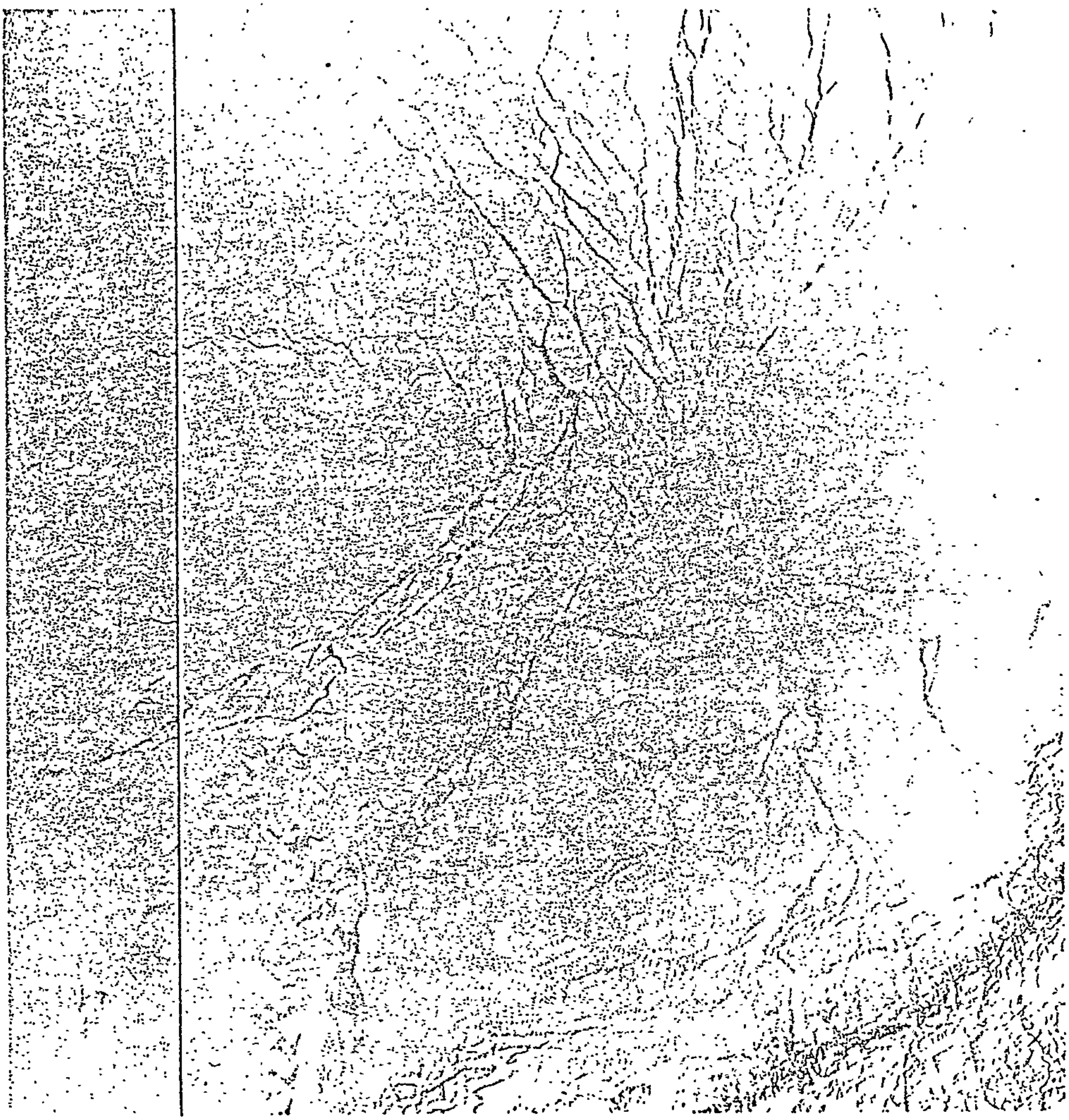

Figure 9. NOAA II image of vicinity of floeberg taken on 8 April 1974. Point Barrow is at center of image.

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The conclusion drawn from this analysis is that during this period the floeberg was responsible for altering the motion of a column of ice approximately 20 km wide upstream and downstream of its position (which remains virtually fixed). However, the previously cited example, March 20/21, 1974 did not exhibit this behavior. In neither case did the presence of the floeberg create a zone of ice exhibiting velocities varying with distance perpendicular to the motion vectors. In both cases, rather than taking place within a zone, shear occurs along well-defined lines.

Ice motions over 18-day period

Still considering meso-scale ice motion effects, it is worthwhile to examine the effect of the floeberg on ice motions observed over the time of a Landsat cycle: 18 days. Figure 10 shows displacement vectors for ice motions between the times of Figures 2 and 7. Hence these displacements include the ice displacements occuring between March 21 and April 7 and also the displacements just considered: April 7 to April 8.

The following table lists the groups of displacemnt vectors and their average deviations:

Group	Location/Description	Average Velocity	Average Deviation
I	Pack ice vectors north of floeberg	3.7 cm/sec	0.1 cm/sec
II	Column of slower vectors upstream of floeberg	1.8 cm/sec	0.2 cm/sec
III	Pack ice vectors south of floeberg	2.5 cm/sec	0.1 cm/sec
IV	Slower moving ice downstream of floeberg	1.6 cm/sec	0.1 cm/sec
V	Block of vectors in lower left of figure	1.1 cm/sec	0.1 cm/sec

This picture shows a column of slower-moving ice apparently resulting from the blockage of pack ice motion by the floeberg. Note that the two zones of pack ice north and south of the floeberg exhibit velocities with a 3:2 ratio over a two and a half week average whereas the one-day ratio was nearly 2:1.

This two and a half week average shows the floeberg slowing a column of ice approximately 26 km wide by almost a factor of 1/2. Here again, shear takes place along lines and not continuously within a zone.

Long Range (1000 km or more)

In the examples just given for influences on meso-scale ice motions by the floeberg it should be noticed that pack ice velocities north and south of the zone of immediate influence were not equal. Figure 9, the NOAA II image obtained at very nearly the same time as Figure 7, shows that the line of shear on which the floeberg is located is part of an extensive crack and lead system. Figure 11, drawn from NOAA II images from April 7 to April 9, 1974, shows the full extent of this system. The vector field shown in Figure 8 shows the Meso-scale ice motion during the 24-hour period ending at the time of Figure 11.

Figures 12 and 13 show barometric data at the beginning and end of this 24-hour period, respectively. On these figures the location of the floeberg is given by a circle and the instantaneous direction of ice motion by arrows. There is a strong suggestion that the large crack and lead system has been generated by an east-moving high pressure area with ice motions nearly along isobars as described by Zubov (1944).

Seldom would one expect to find equal driving forces over a very large area of pack ice. Crack and lead systems result from either unequal driving forces or unequal retarding

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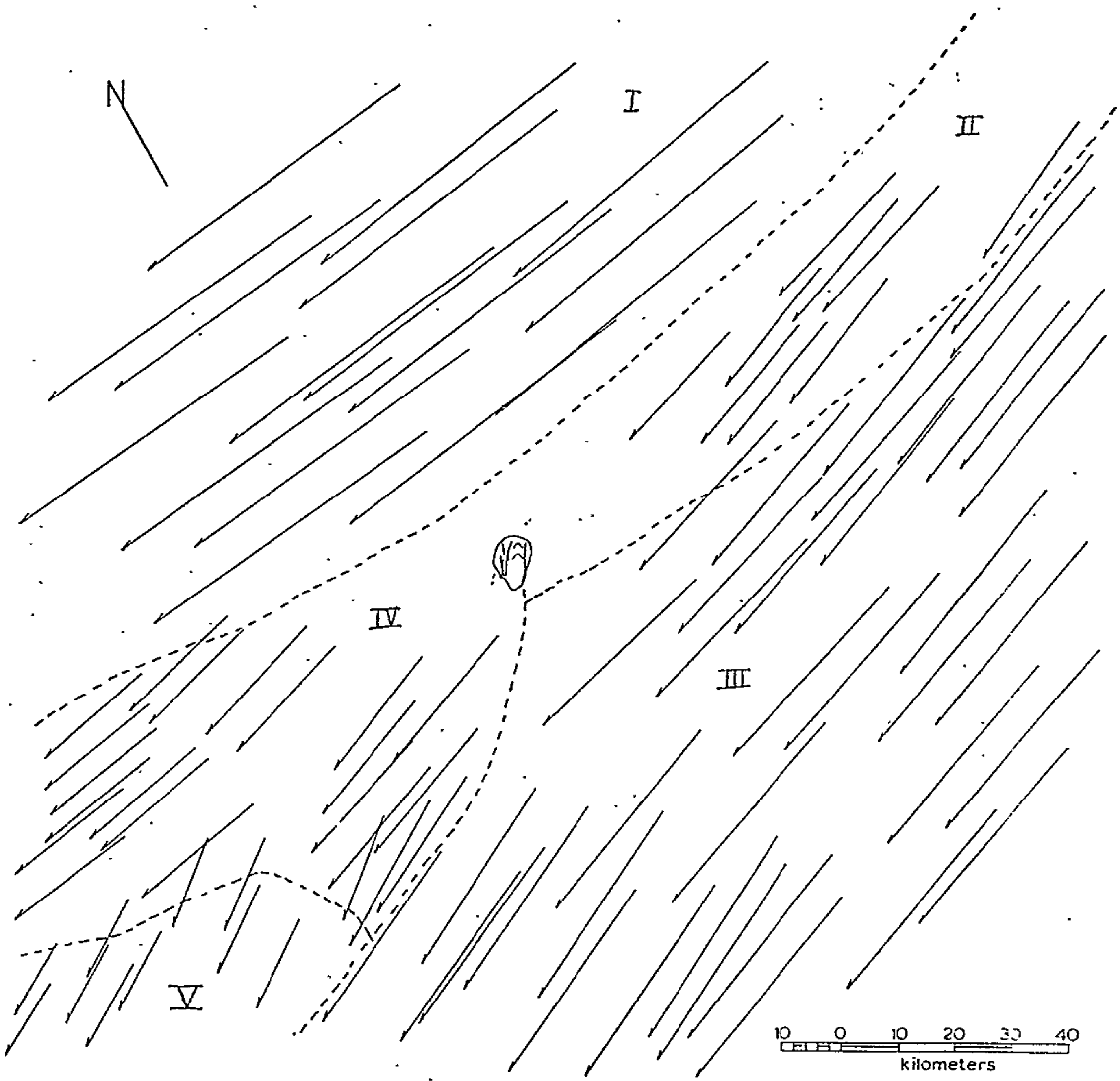

Figure 10. Ice flow vectors for the period 21 March 1974 to 8 April 1974 in the vicinity of "Katie's Floeberg".

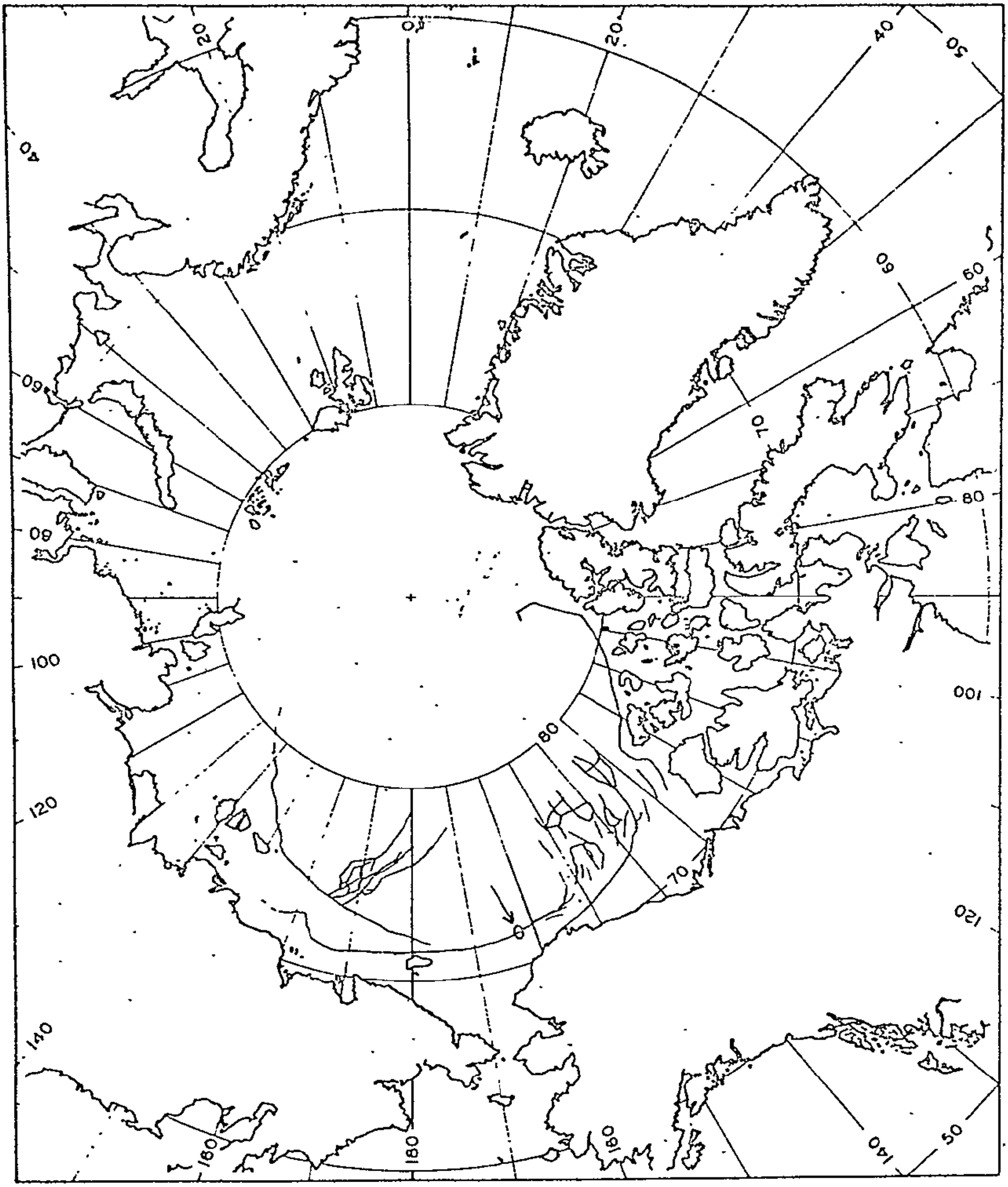

Figure 11. Major lead systems in the western Arctic Ocean, obtained from NOAA II images from 7-9 April 1974.

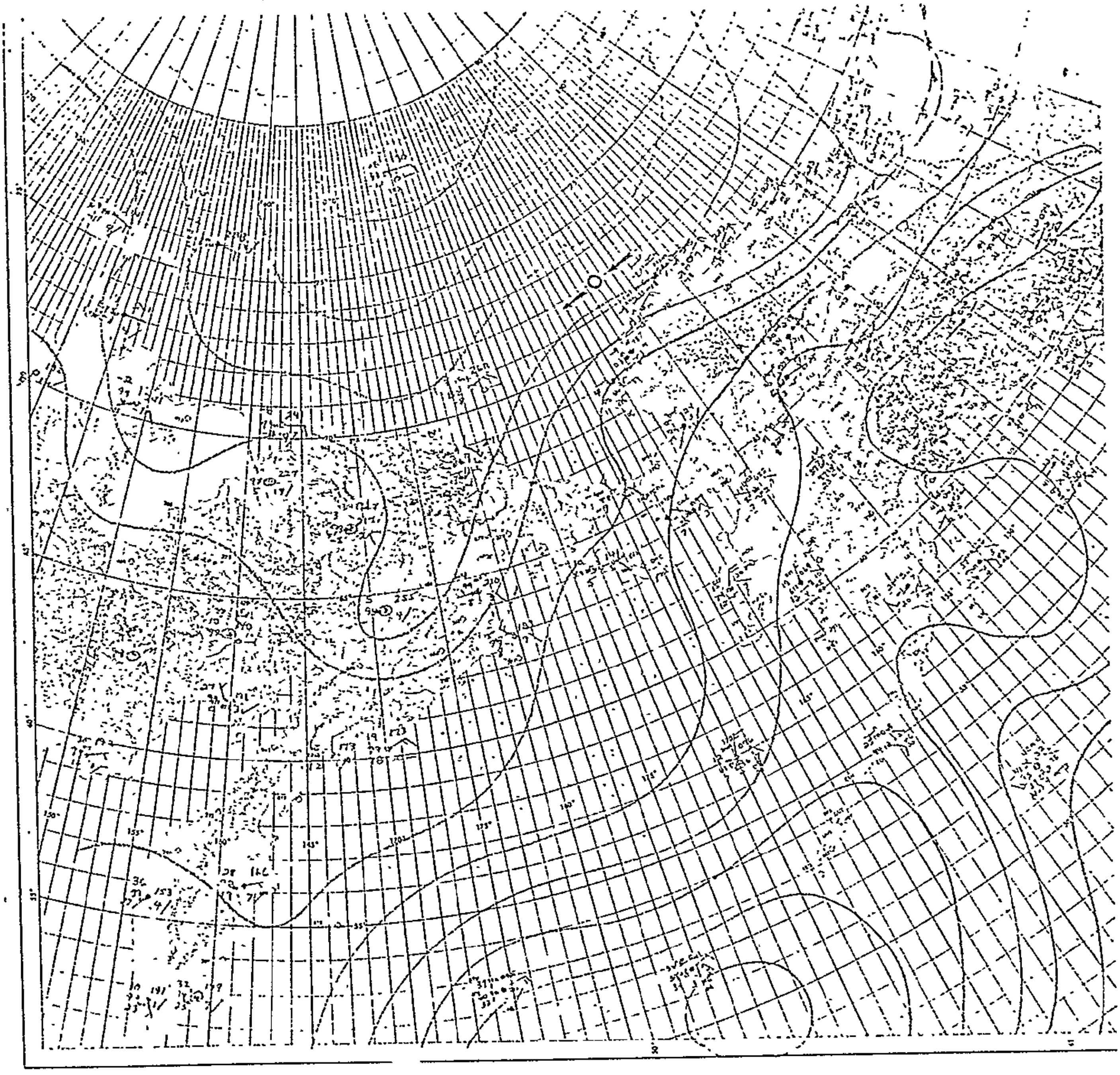

Figure 12. Canadian Environmental Services surface weather chart for 0000 hrs UT, 8 April 1974 showing the location of "Katie's Floeberg" and the observed direction of ice movement.

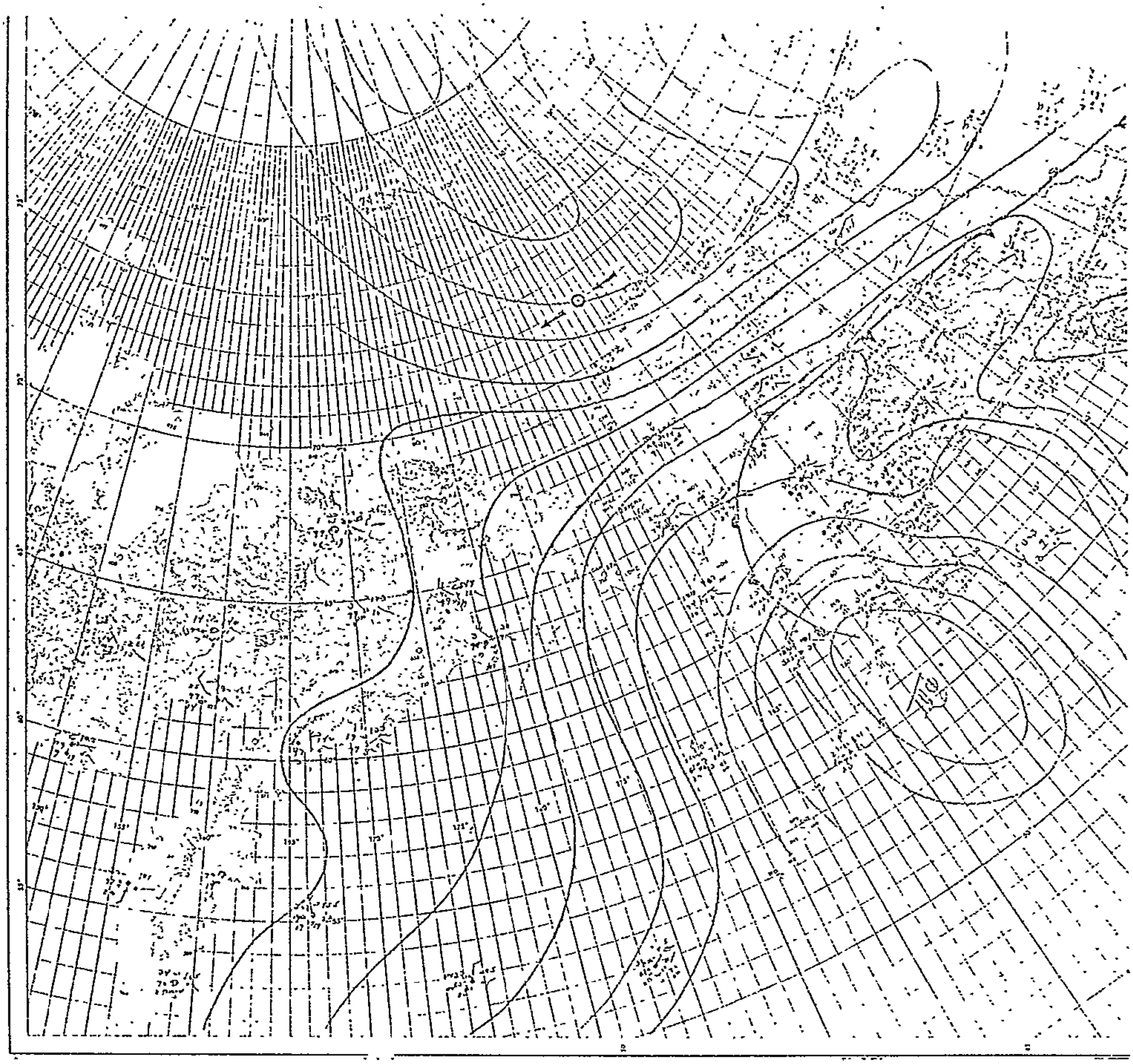

Figure 13. Canadian Environmental Services surface weather chart for 0000 hrs UT, 9 April 1974 showing the location of "Katie's Floeberg" and the observed direction of ice movement.

forces – or both. Hence, given the wind systems suggested by the isobars in Figures 12 and 13 one might expect a long east-west lead separating pack ice to the north and ice perhaps subjected to near-shore drag to the south. In the absence of the floeberg this lead would probably occur somewhere within 50 km of its position shown on Figure 11.

The conclusion drawn here is that the floeberg acts as a stress concentrator defining the location of a line of shear which may extend several hundred kilometers.

Local (within 20-30 km)

One might have expected to observe meso-scale ice motion vectors in the zone of immediate influence to become shorter as the ice approached the floeberg, resulting from compaction of the ice. However, this phenomena is not observed at the meso-scale and so the question arises: does compaction occur at a more local scale?

In order to search for this phenomena Figure 14 was prepared from 1:250,000 scale enlargements of Figures 6 and 7 (Figures 15 and 16) showing ice displacements in the immediate vicinity of the floeberg between March 20 and 21, 1974. Wherever large floes could be identified, they were drawn in so that the viewer could make the distinction between vectors drawn for the motion of individual floes and vectors drawn for different points on large floes. (Note that in the latter case two unequal or non-parallel vectors indicate rotation as well as translation of the floe.)

Examining this figure it appears that the motion of floes on either side of the floeberg (transverse to the direction of floe motion) is not significantly altered in its immediate vicinity, except for a slight tendency on the south side to diverge upstream and converge again downstream. The three equal and parallel vectors terminating on the floe just north of the floeberg indicate that this floe is not rotating and is therefore not in a region of shear. Shear is therefore confined to the narrow region between this floe and the floeberg. Although the vectors on the south side of the floeberg exhibit the divergence – convergence pattern mentioned earlier, there is no evidence of shear taking place any closer than these vectors.

Upstream of the floeberg there is evidence of blockage of ice motion. On the north side there are three short vectors which, by their pattern indicate that these floes have been slowed considerably and are being deflected around the north side of the floeberg. Just to the south of the vectors, a large floe is approaching the floeberg and is rotating clockwise. However, vectors drawn on opposite sides of a large floe located further upstream show no sign of its being rotated or slowed upon its approach to the floeberg. Vectors located between these floes show evidence of smaller floes being deflected somewhat around the rotating floe.

CONCLUSIONS

It would be useful to tabulate the conclusions regarding pack ice driven past an isolated obstruction drawn from analyses at the three distance scales.

1. Large scale (regional). The obstruction may act as a "stress concentrator" influencing the location of major components of large lead systems.

2. Meso-scale. Pack ice driven past the obstruction can be broken into two sheets of ice moving with essentially unaltered velocities and a column of slower-moving ice between the two sheets containing the obstruction. Under these circumstances, the width of the column of ice directly affected by the obstruction is on the order of 3 times the cross-section presented by the obstruction. Ice within this column is subjected to considerable breakage. (Individual pieces of ice become difficult

Figure 14. Ice flow vectors showing local ice motion in the vicinity of "Katie's Floeberg" for the period 20-21 March 1974.

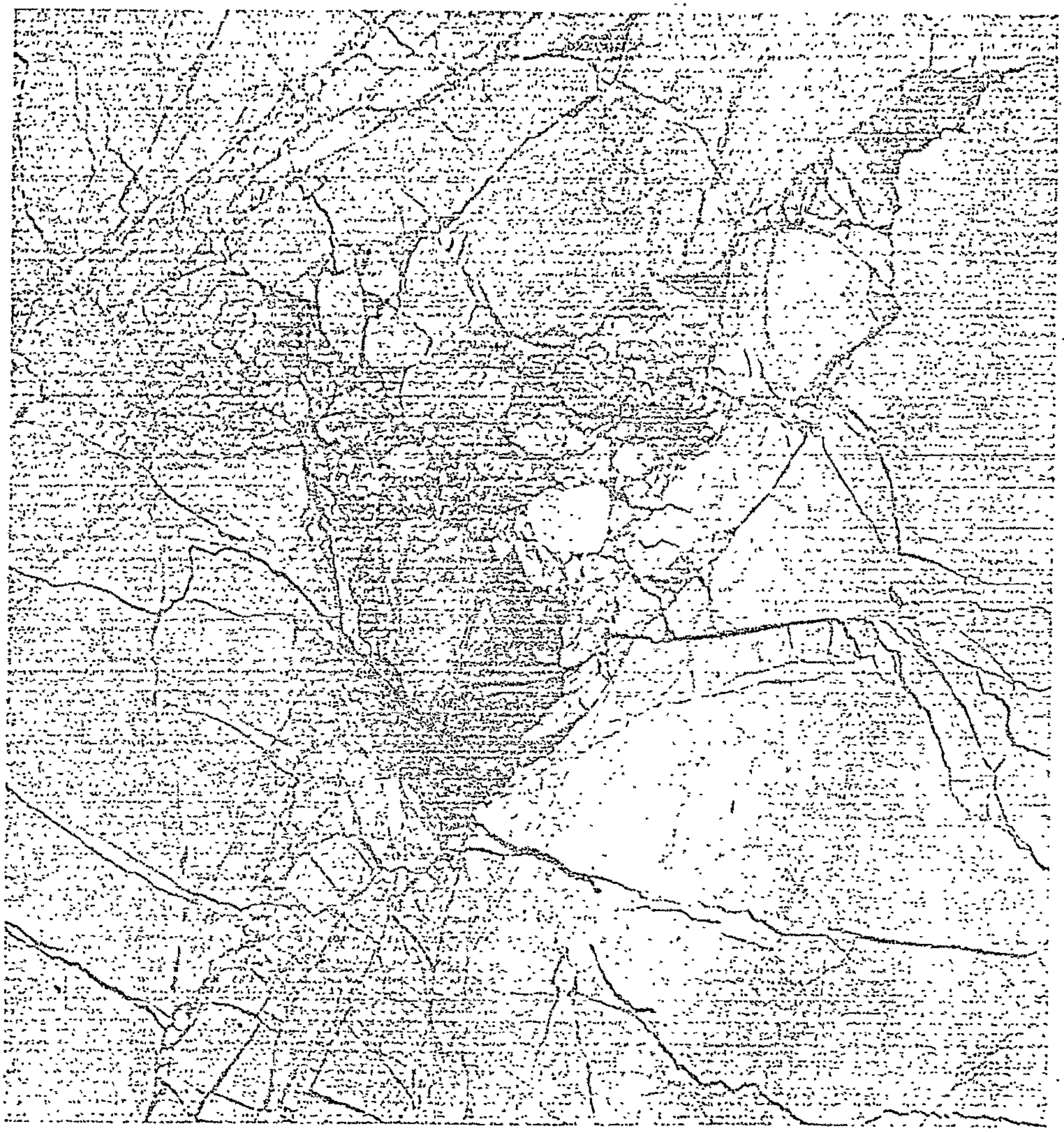

Figure 15. Enlarged Landsat I image of 20 March 1974 UT, at approxiamtely 1:250,000 scale.

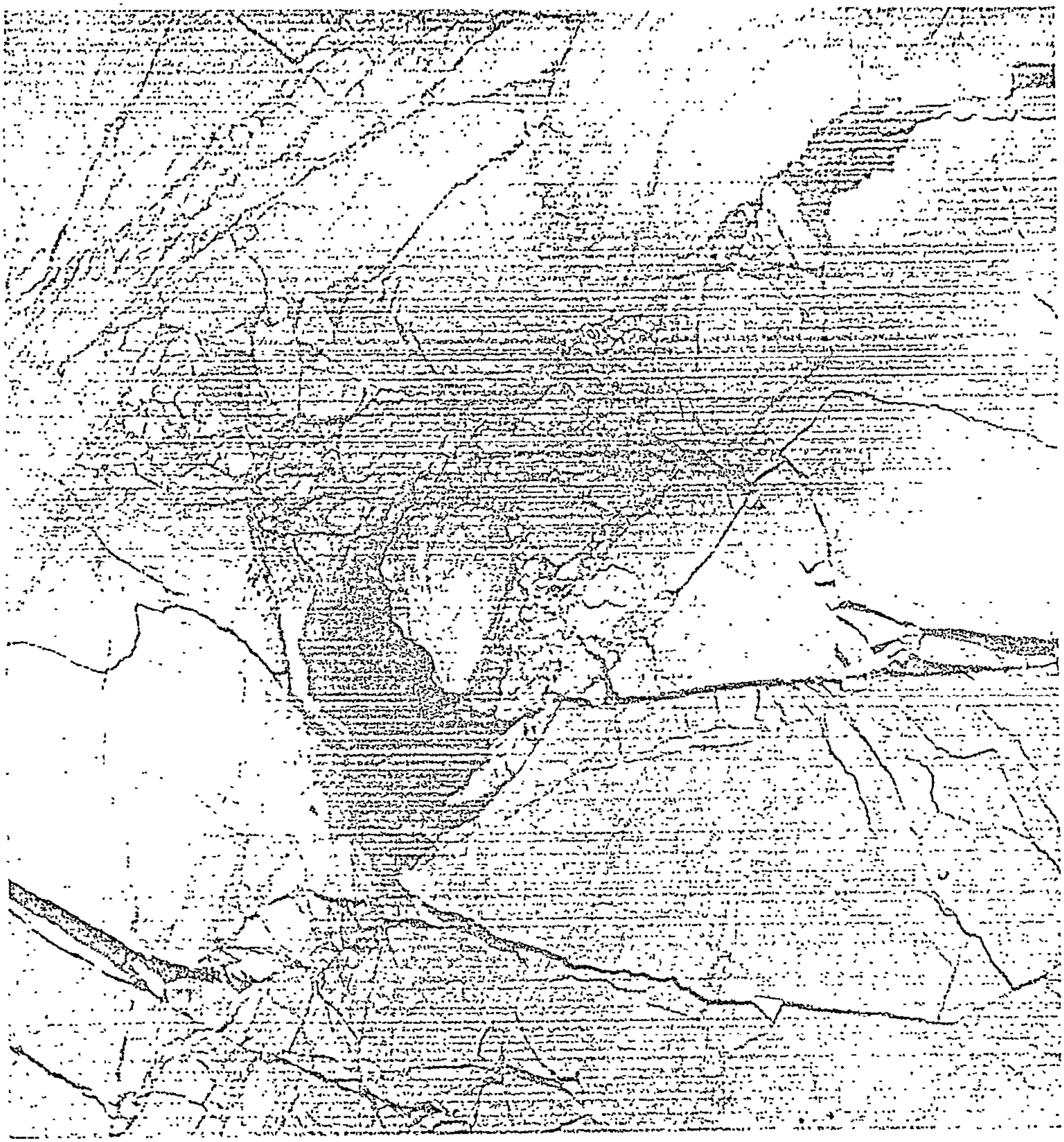

Figure 16. Enlarged Landsat I image of 21 March 1974 UT, at approximately 1:250,000 scale.

to distinguish from one Landsat scene to the next as they approach the obstruction.)

Differental motion takes place entirely along the boundaries of the breaking zone. In this respect the concept of an instantaneous "shear zone" does not really apply - rather it would be more appropriate to describe differential motion taking place along "lines of shear".

3. Small (local) scale. As ice within the breaking zone approaches the obstruction the velocities of smaller pieces of ice decrease. This effect only appeared to propagate as far as twenty kilometers upstream of the obstruction.

The width of the breaking zone does not increase at the location of the obstruction. Hence, since the breaking zone is approximately 3 times as wide as the obstruction, under steady-state conditions, ice within the breaking zone column must be on the average half again as thick when moving past the obstruction as when farther than twenty kilometers upstream. This estimate assumes that ice moves past the obstruction at the average velocity of the breaking zone column.

Implications to Offshore Petroleum Development

Considerable attention has been given to the possibility of construction of permanent structures on the continental shelf for activities related to petroleum extraction. Here we will consider the conclusions just discussed in terms of such structures.

The implications to be drawn from the conclusions regarding effects on large-scale ice motions is that even one structure could determine the precise location of a major lead, assuming that the force pattern was such that a lead was about to be created in the vicinity. (Here we are discussing a lead, resulting from differential stress within the ice pack, which may be 1000 km in length and not the actual track of the structure in the ice pack.) If the structure is located far from shore the picture could be very similar to that presented by the floeberg; the structure would be surrounded by moving ice. However, if the structure were located near shore, it might determine the position of the flaw lead and thereby alter the extent of ice stationary with respect to the shore. The alteration would very likely be such as to increase the extent of this ice.

The conclusions drawn from meso-scale considerations show that under the proper conditions, not only would the track of the structure extend "downstream" (as would be expected) but also the "breaking zone" column would extend "upstream" from the structure. Obviously the cross section of the structure would influence the width and length of this zone in a direct way. Taken together, the track and breaking zone related to the structure would be responsible for considerable amounts of open water and thin ice in the vicinity of the structure. Of course, the magnitude of this effect would be dependent on pack ice motion.

It would be interesting to consider a further implication of this phenomena. The large amount of open water and thin ice in the vicinity of such a structure could act to attract sea mammals (and their predators) and could possibly prove to be beneficial to sea mammal existence. On the other hand, petroleum spills originating at the structure would almost certainly collect in these adjacent areas, and possibly prove harmful to the animals congregated there.

The local scale conclusions imply that often the structure would almost certainly be surrounded by moving pressured ice - except on the side of the downstream polynya - and direct surface travel to and from the pack ice would often be impossible. Even in the event that pack motion ceased, whenever the motion resumed, the structure would very quickly become isolated from the pack ice.

These conclusions would suggest that serious and careful considerations should be given to the location of an off-shore structure placed within the moving pack ice region, and its possible effects on marine mammals.

Acknowledgements. The research reported here was supported in part by NAS5-20959 and OCS 03-5-022-55.

REFERENCES

Zubov, N. N., Arctic Ice, translation by U. S. Navy Oceanographic Office and the American Meteorological Society under contract to the Air Force Cambridge Research Center, 1963, Published by Naval Electronics Laboratory (San Diego), 491 pp.

APPENDIX B.

Ice Hazards to Offshore Oil Operations in Arctic Alaskan Waters.

To be presented at the 31st Annual Petroleum Mechanical Engineering Conference, Mexico City, September 16-19, 1976. To be printed in this form by the conference by an appropriate journal.

Ice Hazards to Offshore Oil Operations in Arctic Alaskan Waters†

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I. Introduction

Sea ice presents a hazard to offshore drilling structures and associated support activities which can exceed the normal hazards of winds and waves by a considerable margin (Hudson, 1973). Fortunately, along much of the Arctic coastline the ice is grounded during the last half of the winter, exerting only nominal internal stresses (Nelson et. al., 1976). However, under breakup circumstances, this nominally shore-fast ice can acquire velocities of 2 m/sec or more (Sackinger et. al., 1974), and under such circumstances is likely to produce stresses which may be as great as those experienced in the moving ice pack.

Locations with more extreme ice hazards are found beyond the boundary of the shorefast ice, on the prevailing sides of coasts and islands, and in relatively deep ($\geq$ 20 m) unsheltered water where the ice moves virtually continuously. The proposed Outer Continental Shelf lease sale areas in the Bering, Chukchi, and part of the Beaufort Sea are largely in this latter category. It is obviously important to document the regions of relatively safe, shorefast ice, and a study of LANDSAT (Land Imaging Satellite) imagery is currently in progress to do so. The dynamics of the shorefast breakup events are also being studied using time-

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lapse photography of the screen of the University of Alaska sea ice radar at Barrow, Alaska.

In this paper, we describe the annual cycle of Beaufort Sea near-shore ice events and discuss the possible hazards related to these various ice conditions.

II. Beaufort Sea Near Shore Ice Conditions

Usually the Beaufort Sea coast is ice-free during August and September. Ice formation begins in October and generally does not form a dependably stable surface until late December or early January. The stable surface, when formed, is usually referred to as "shorefast ice". Although several slightly differing definitions of "shorefast ice" are in common usage, the term generally refers to ice stationary with respect to the shore and bounded by grounded ice features (shear and pressure ridges, floebergs, stamukhi, etc.) (see Kovacs and Mellor, 1974).

The processes at work during the formation of shorefast ice are not well-documented, largely because they have not been at the focus of attention. These processes occur during the dark winter months, when satellites with high resolution visible spectrum sensors are not operative.

However, it is known that the formation of the fast ice usually takes place in stages, often punctuated with episodes of wind-driven ice being piled and compacted into successive bands parallel to the coast. Many of these features are grounded and serve to anchor the surrounding ice in place. This anchoring effect seems to function to a water depth of approximately 20 m. Hence, the 20 m bathymetric contour is usually taken to be the nominal seaward limit of Beaufort Sea shorefast ice.

Dynamic ice events can and do occur within the "shorefast" zone before the ice becomes sufficiently anchored to be reliably stable. Although these events are presently unobservable by means of imaging satellites, other techniques exist, which although limited in comprehensive geographic coverage, give detailed information. One of these techniques is imaging radar.

Radar has proven to be a valuable tool for the study of the dynamics of shorefast ice during formation and breakup.. The University of Alaska sea ice radar facility was established at Point Barrow in March 1973, supported jointly by the Alaska Oil and Gas Associations and the Alaska Sea Grant Program. Using time-lapse photography of a conventional cathode ray tube display, it has recorded the motion of sea ice for over three years.

A particularly severe and unusual breakup event has been analyzed by Shapiro (1975). Until 26 December 1973, the ice was landfast out to beyond the 20 meter water depth contour. An offshore wind in the range 13-24 km/hr prevailed for 15 hours when, at 0545 U.T. on 26 December, the ice broke free and drifted away from the coast at 0.7 km/hr. The windspeed reached 30 km/hr at that time. The time-lapse film shows subsequent ice flow motion parallel to the shoreline at 3.7 km/hr.

Subsequently, on 31 December, the wind velocity increased to 90 km/hr (with gusts to approximately 150 km/hr) parallel to the shoreline. The ice drift velocity increased to 8.3 km/hr, parallel to the shore, and impact of this drifting ice was sufficient to drive out other ice floes which had grounded on shoals earlier. This sequence represents the most severe condition of drifting ice in the shorefast zone which has yet been analyzed.

In order to illustrate the optically observable portion of the annual cycle of near-shore ice dynamics, a sequence of Landsat scenes showing the vicinity of Prudhoe Bay, Alaska in 1974 will be used. Near-shore ice forms during the dark months when there is insufficient light for Landsat imagery to be obtained. Typically, the earliest Landsat scenes of the Prudhoe Bay area are available in late February or early March. Figure 1, obtained on March 10, shows the already formed "shorefast" ice and evidence of shearing motions in the pack ice beyond. Because no imagery is available from the period of fast ice formation, knowledge of that period must be gleaned from this earliest scene.

Close examination of this Landsat scene shows several discontinuous bands of similarly textured or shaded ice more or less parallel to the coast. These bands represent various stages in the "freeze-up" of the near-shore ice. The stages represented include freezing in place, compaction, piling and rafting of ice frozen in place, and piling and rafting of newly-formed or multi-year pack ice driven into the near-shore area. The boundaries of each of these bands were each once the seaward edge of the ice, fixed with respect to the shore, and could have been the site of formation of shear or pressure ridges for some period of time.

Each boundary is located in successively deeper water and hence could be subject to more severe ridging conditions. Just seaward of the most pronounced bands a series of large, massive shear ridges can be identified on the imagery. These too, formed during "freeze-up". However, as will be seen, these ridges are well shoreward of the location of shearing conditions by the date of this image.

The most visible indications of shear are the newly-formed and refrozen lead systems running somewhat parallel to the coast. Examining first the older, now refrozen, lead it can be seen that its formation involved displacement of the pack ice to the east a distance of several kilometers. Further, the pattern exhibited by the other refrozen leads is that of stress relief, showing that the strain release was not limited to the slippage along this lead. The appearance of the outermost of these refrozen leads indicates that after formation of this system of leads, there may have been some westward slippage of the pack ice beyond this lead, thereby opening it up.

Now, on March 10, after this lead system has frozen over, a lead system is forming. This new lead system indicates westward displacement along two lines: The outermost coincides with the outermost of the former lead system and the inner lead runs for some distance within the more shoreward of the refrozen leads, but then strikes off slightly seaward of the former lead.

This image, then, illustrates the concepts of "shorefast" ice and the active "shear zone".

The next Landsat image available for this area was obtained on March 28, (Figure 2) during the succeeding Landsat cycle. Where formerly the ice exhibited a displacement gradient with westward displacements increasing with distance from shore, it appears that sometime during this eighteen day interval, the ice seaward of the most shoreward of the old lead system has moved several kilometers westward as a block, largely obliterating the old refrozen lead. Presumably during this time a pressure ridge of considerable magnitude was created. Examination of imagery

from the summer melt season will show that the ridges formed during this event persisted into that period.

The next Landsat data would have been obtained in mid April but this image is not available - probably due to excessive cloud cover. The May 3 image (Figure 3), obtained on the second Landsat cycle after the late March scene, shows that little, if any, change has taken place other than perhaps further compression of the refrozen leads. Hence, during this period of over one month, Beaufort Sea ice off Purdhoe Bay was not subject to conspicuous shear or breakage for at least fifty miles offshore. Apparently this is a somewhat common occurrence, having been observed the previous year also (see Stringer, 1974).

On the west side of this image is an oblong ice feature which, while extant on the earlier images, can be examined for detail for the first time this season on the Landsat image under discussion. This grounded hummock field appears to be a recurring feature and has been reported earlier (Stringer, 1974), based on 1973 observations. An aerial reconnaissance of this feature was performed in July, 1974 which confirmed the nature of this feature. There is reason to believe that this feature and Katie's Floeberg (Stringer and Barrett, 1975) are the result of similar processes and represent essentially the same general type of ice feature. Note that lead systems are strongly deflected around this feature, indicating the major role played by its existence. On subsequent scenes it will be seen that the boundary of shorefast ice was seaward of this feature.

The next available Landsat image was obtained on May 21 (Figure 4). Here, the ice exhibits a marked change over the previous image. Whereas before this date the polar ice off Prudhoe Bay formed mainly a sheet

continuous with the shorefast ice, now the polar ice is breaking up. This general behavior has been observed on imagery from other years at this date. However, it may be unusual for the pack ice to be broken up with such large voids between individual pans. Obviously at this time the "shear zone" begins at the boundary of the ice continuous with the shore and the open water. On the west side of the image, the shear boundary nearly coincides with the boundary defined by much earlier ice activity but it is still actually somewhat seaward of this location. The grounded hummock field mentioned earlier is located at this point and it is worthwhile to note that this feature remained within the shear boundary. Our contention is that this feature was a factor in determining the shear boundary.

The shear boundary runs nearly eastward across the image, increasing its distance from shore and the edge of the shorefast ice toward the east. It is not uncommon for the shear boundary to coincide with the edge of shorefast ice at this time, however (see Stringer, 1974).

The next Landsat imagery of Beaufort Sea ice off Prudhoe Bay is available for June 25 and 26 (Figures 5 and 6). By this time, the Beaufort Sea pack ice is well broken up and moving. Examination of the Landsat images for these dates shows that there is a definite boundary between moving and non-moving ice. Further, this boundary coincides with the shear and pressure ridges observed under construction in late March. The late June images are especially useful for examination of the make-up of the ice within the boundary mentioned. Many authors consider this ice "shorefast ice" but this definition is not held universally. Melting conditions have removed most of the snow cover from the ice, showing for the first time the detailed structure of the ice which was obscured

on previous imagery. Here, the successive bands of ice within the shorefast zone can be examined for clues about their origin and alterations. It can be seen that some bands appear to consist of uniform sheets of ice which probably formed in-situ, while others consist of compacted blocks of ice which were formed elsewhere and driven into their present location. Hence the "freeze-up" of the shorefast zone was a dynamic event bringing highly variable ice conditions. We have seen that radar observations of shorefast ice formation at Barrow generally corroborate this behavior.

By July 14 when the next Landsat image is available, Figure 7, considerable deterioration of the shorefast ice has taken place. Near shore - particularly near river mouths - it has melted completely, while seaward, particular pans and areas of pans have melted. Hummock field, shear and pressure ridges become more distinct due to their persistence.

The last Landsat image for the Prudhoe Bay area in this year was obtained on September 6 (Figure 8). It shows the near-shore areas free of ice and the polar ice pack far beyond. Between the coast and the pack ice are several groups of floes which appear to be stranded at locations far offshore. Evidence supporting the contention that these groups of floes are stranded can be found in that other floes are passing around them toward the west exhibiting typical slip-stream patterns. This is not an uncommon occurrence (Reimnitz, 1976) and results when a few pieces of ice of deep draft become grounded (or remain from the previous ice season). Currents and winds cause other ice floes to pile up against them. Brooks, (1974), studied one occurrence of this phenomena and remarked on the relatively small number of grounded

obstructions required to produce this effect. Presumably ice of this nature can persist into the next year's ice season. However, this is not always the case, as demonstrated by the October 4, 1972 image.

The October 1972 image (Figure 9), although not related to the sequence described above, demonstrated early freeze-up conditions. From this image, it can be seen how the near-shore ice forms in successive bands. Although young ice may be formed over quite an extensive area, only the most protected ice remains fixed in location. Portions of new ice are broken off and drift under the influence of wind and currents. This mechanism repeats successively during the freeze-up period, accounting for the many bands of differently textured ice in the near-shore areas.

III. Discussion

It can be seen that throughout the year there are a series of ice conditions representing hazards to operations related to offshore petroleum exploration and extraction activities. These will be discussed in terms of each season.

Freeze-up: (October - January) During this time there is not a clear distinction between a shorefast zone and pack ice. Hummock fields, shear and pressure ridges form in all near-shore areas, providing load-bearing surfaces with large cross-sectional areas. Consequently large forces may be impressed on obstructions to ice motion regardless of their location. It would be extremely difficult, for example, to maintain a barge or drill ship in a desired location during this time. Modes of travel to offshore locations would be restricted to airborne methods. Bottom-fast structures may be subjected to rather large lateral forces.

Post Freeze-up: (February - April) The most stable ice conditions are found during this time. Once the grounded features which define the

shorefast zone are established, that area becomes suitable for surface travel. Further, bottom-fast structures within this area could be protected from large forces even if they did develop in that zone by means of a number of artifical strain-release mechanisms. (For instance, explosives could be used to eliminate physical continuity of the ice.) During this period there is also the greatest likelihood of stability of ice beyond the shorefast ice ... perhaps affording a temporary platform for seismic exploration.

Spring: (April - May) Shear becomes active along the edge of the shorefast ice. There is some danger of transmission of forces to points within the shorefast ice and consequent strain release within this zone (Stringer, 1974). Beyond the shorefast ice, great lateral forces can be exerted by moving pack ice.

Melt season: (June - July) Shear continues beyond the shorefast ice. Within the shorefast zone, ice movement takes place by non-grounded ice. Although such an occurrence has not been observed on the satellite data, it has been observed by radar (Sackinger et. al., 1974). Severe ice conditions may develop within the shorefast zone resulting from summer storms.

Ice-Free Season: (August - September) This period is generally the span of time that the coastal area is ice free. However, this condition is not entirely dependable as was demonstrated by the September 6, 1974 image (Figure 8). During this time the entire coastal area is prone to severe ice conditions resulting from storms. The well-known Beaufort Sea storm surge beach ridges offer testimony that these events do occur.

It is interesting to speculate on the effect of a number of man-made structures placed in the near-shore areas. If placed within the present shorefast zone, the effect could be that of increased hummocking in their

vicinity and greatly increased stability of the ice sheet within the perimeter defined by the structures. In the extreme case there might be a tendency for the ice within this perimeter to become permanent. If placed beyond the present boundary of shorefast ice, man-made structures could very likely move the edge of shorefast ice out to that location. In either case, in the ice-free season the structures would serve the same purpose as the grounded ice fragments during that period and result in large groups of ice floes forming a barrier to seaward.

IV. Implications: Effects of Ice on Offshore Operations

If petroleum exploration is initiated from floating drillships, as is planned for the Canadian Beaufort Sea in the summer of 1976, drilling can proceed only during the ice-free (less than 10% ice cover) periods. Based upon the limited number of years of satellite and aircraft observation data available, this can range from approximately 8 months in the St. George Basin of the Bering Sea to a mean of 28 days in the Prudhoe Bay area of the Beaufort Sea. Anomalous weather conditions can shorten or segment these ice-free periods, as occurred in the summer of 1975 in the Beaufort Sea. Ice-reinforced drilling and resupply vessels would permit an extension of the drilling time and should be seriously considered. Exploration from gravity structures which could resist ice pressure would result in longer working periods, but platform service and resupply access would be primarily by helicopter, hovercraft, or in the case of shorefast ice - by wheeled vehicles over the ice after mid-winter. The shorefast ice zone is the safest region for winter drilling operations. On the prevailing side of coasts and islands, or indeed beyond the shorefast ice in water deeper than 20 meters, ice pressures are more severe and virtually continuous.

Eventual production would require the development of subsea production equipment which can withstand occasional ice scour. Continuous petroleum production throughout the year from the western coast of Alaska will be likely to require a fleet of ice-reinforced tankers, as well as an ice-resistant deepwater loading terminal offshore. For the annual ice encountered in the Bering Sea, this appears to be within the capabilities of present technology, although the existence of sufficient reserves, together with the economics of the situation, remain to be determined. The relationship between ice motion and meteorological variables would be operationally important, so that accurate ice forecasts could be made.

ACKNOWLEDGEMENTS

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REFERENCES

Brooks, L. D., Ice Scour on Northern Continental Shelf of Alaska, Proceedings of the Symposium of Beaufort Sea Coast and Shelf Research, Arctic Institute of North America, 355-366, 1974.

Hudson, T. A., Arctic Offshore Data Gaps and How to Fill Them, Offshore Technology Conference, Houston, Texas, May 1973.

Kovacs, A. and M. Mellor, Sea Ice Morphology and Ice as a Geologic Agent in the Southern Beaufort Sea, Proceedings of the Symposium on Beaufort Sea Coast and Shelf Research, Arctic Institute of North America, 113-162, 1974.

Nelson, R. G. and W. M. Sackinger (1976), Stresses in Sea Ice, 31st Petroleum ASME Conference, Mexico City, September, 1976.

Reimnitz, E., L. Toimil, and P. Barnes (1976), Development of the Stamukhi Zone and Its Relationship to Arctic Shelf Processes and Morphology, Beaufort Sea, Alaska. (Preprint)

Sackinger, W. M., J. C. Rogers, and R. D. Nelson, Arctic Coastal Sea Ice Dynamics, Offshore Technology Conference, Houston, Texas, May 1974.

Shapiro, L. H., A Preliminary Study of the Formations of Landsat Ice at Barrow, Alaska, Winter 1973-1974, Geophysical Institute Report UAG R-235, Sea Grant Report No. 75-7, June 1975.

Stringer, W. J., Shorefast Ice in the Vicinity of Harrison Bay, The Northern Engineer, Vol. 5, No. 4, Winter 1973/1974.

Stringer, W. J. and S. A. Barrett, Ice Motion in the Vicinity of a Grounded Floeberg, Proceedings of the Third Conference on Port and Ocean Engineering Under Arctic Conditions, University of Alaska, in press, 1976.

Stringer, W. J., The Morphology of Beaufort Sea Shorefast Ice, Proceedings of the Symposium on Beaufort Sea Coast and Shelf Research, Arctic Institute of North America, 165-172, 1974.

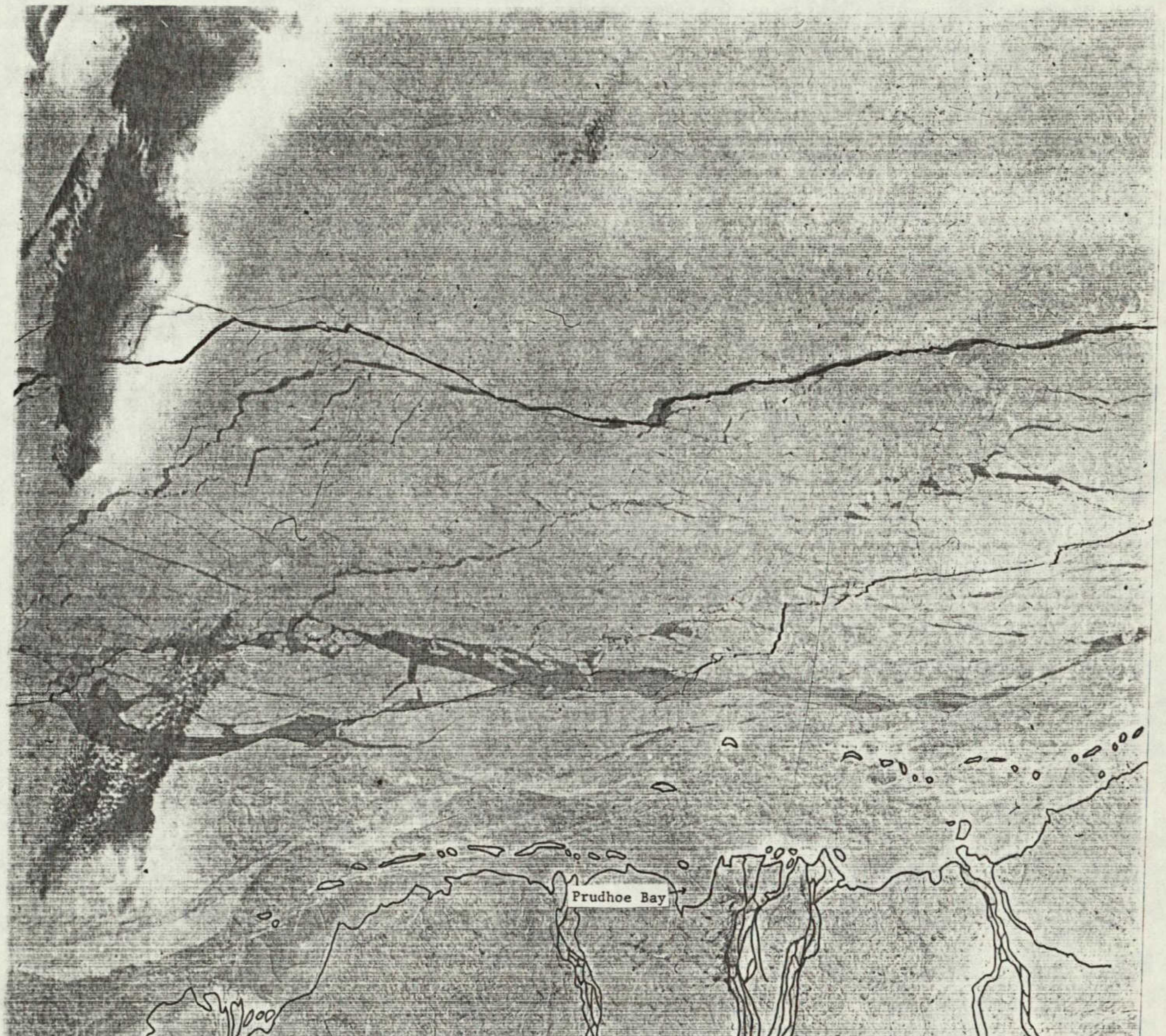

Figure 1: Landsat image 1595-21180 obtained 10 March,1974 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.

Figure 2: Landsat image 1613-21174 obtained 28 March,1974 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.

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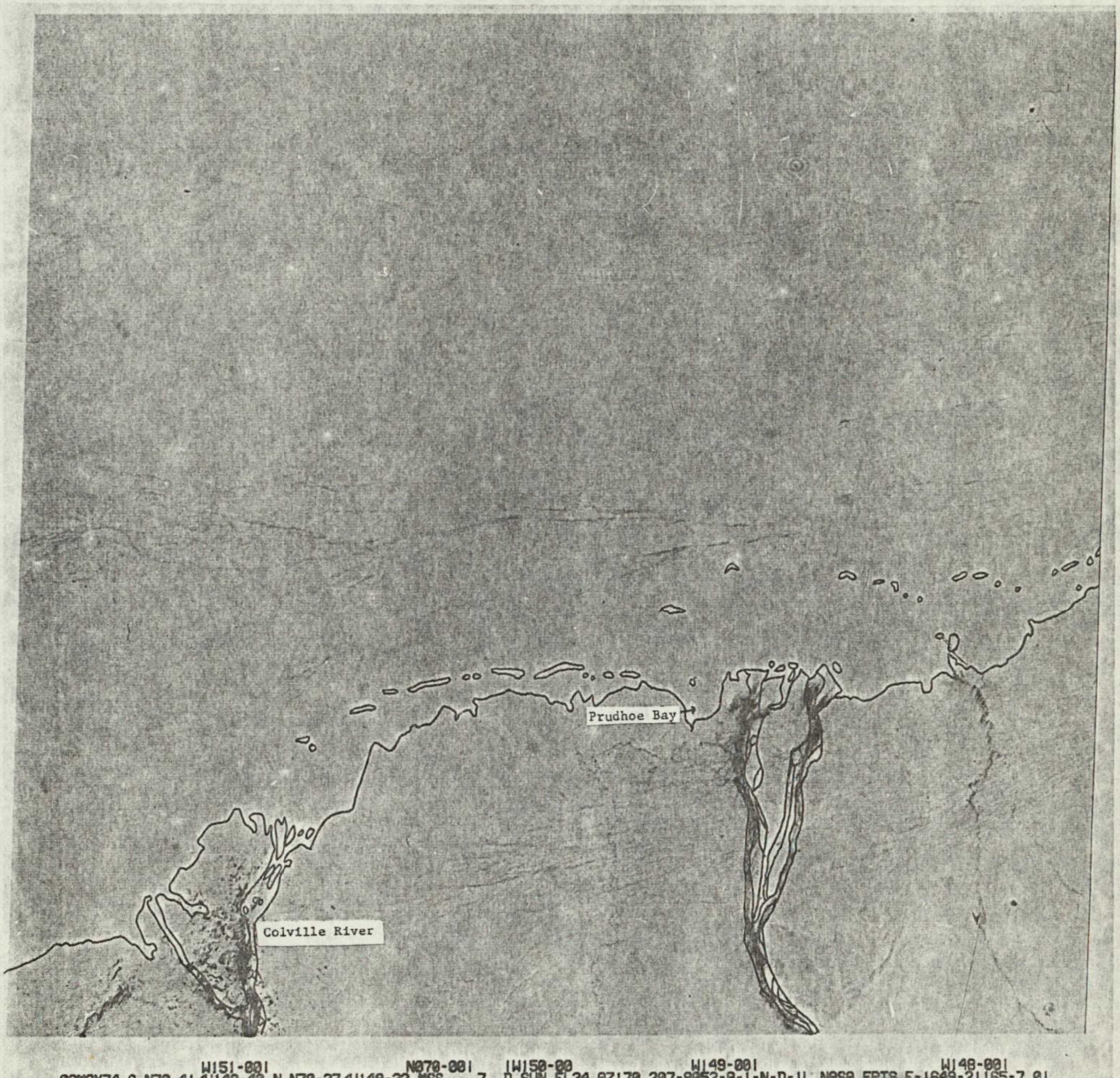

Figure 3: Landsat image 1649-21165 obtained 3 May,1974 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.

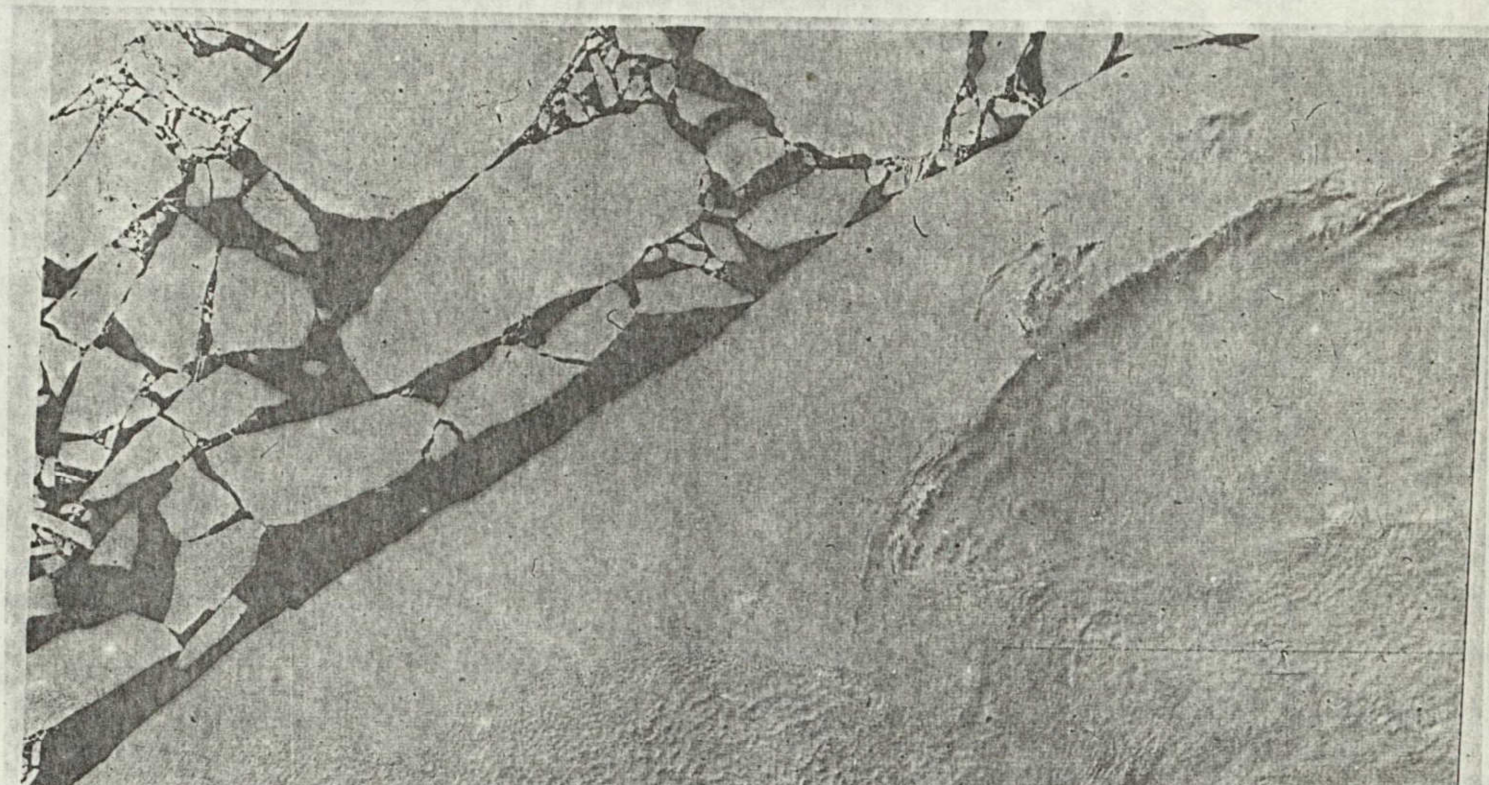

Figure 4: Landsat image 1667-21162 obtained 21 May,1974 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.

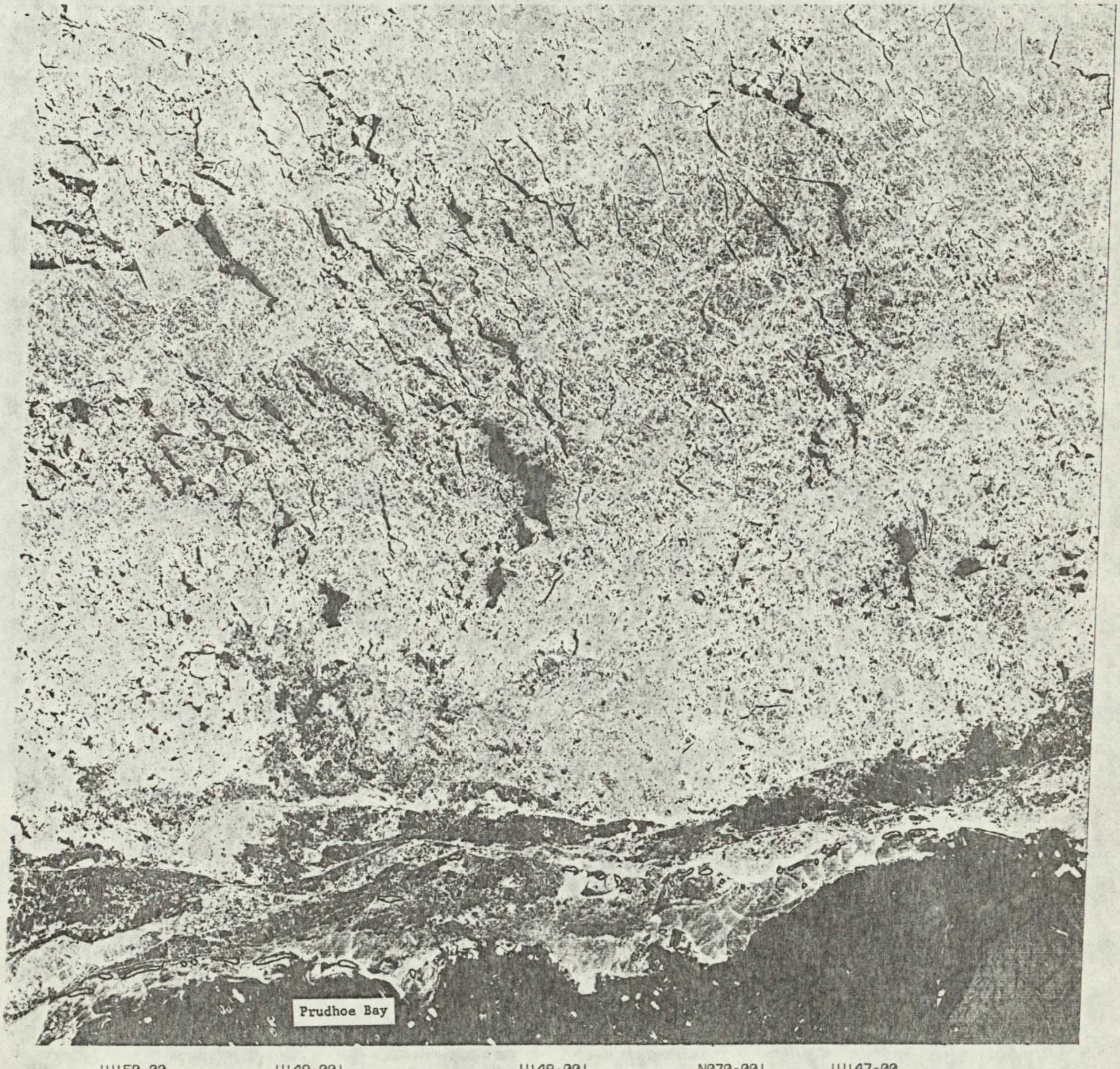

Figure 5: Landsat image 1702-21093 obtained 25 June,1974 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.

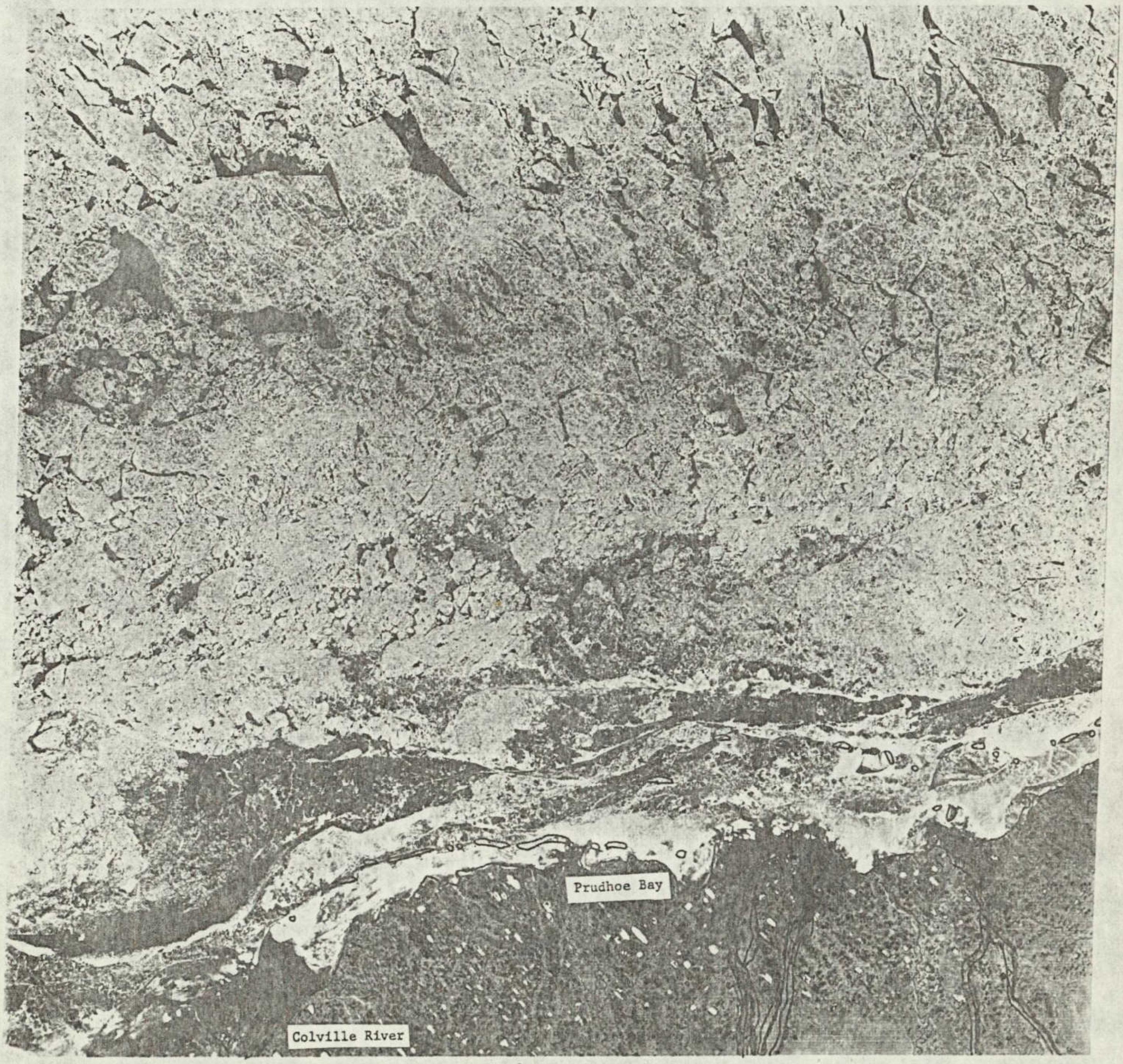

Figure 6: Landsat image 1703-21151 obtained 26 June,1974 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.

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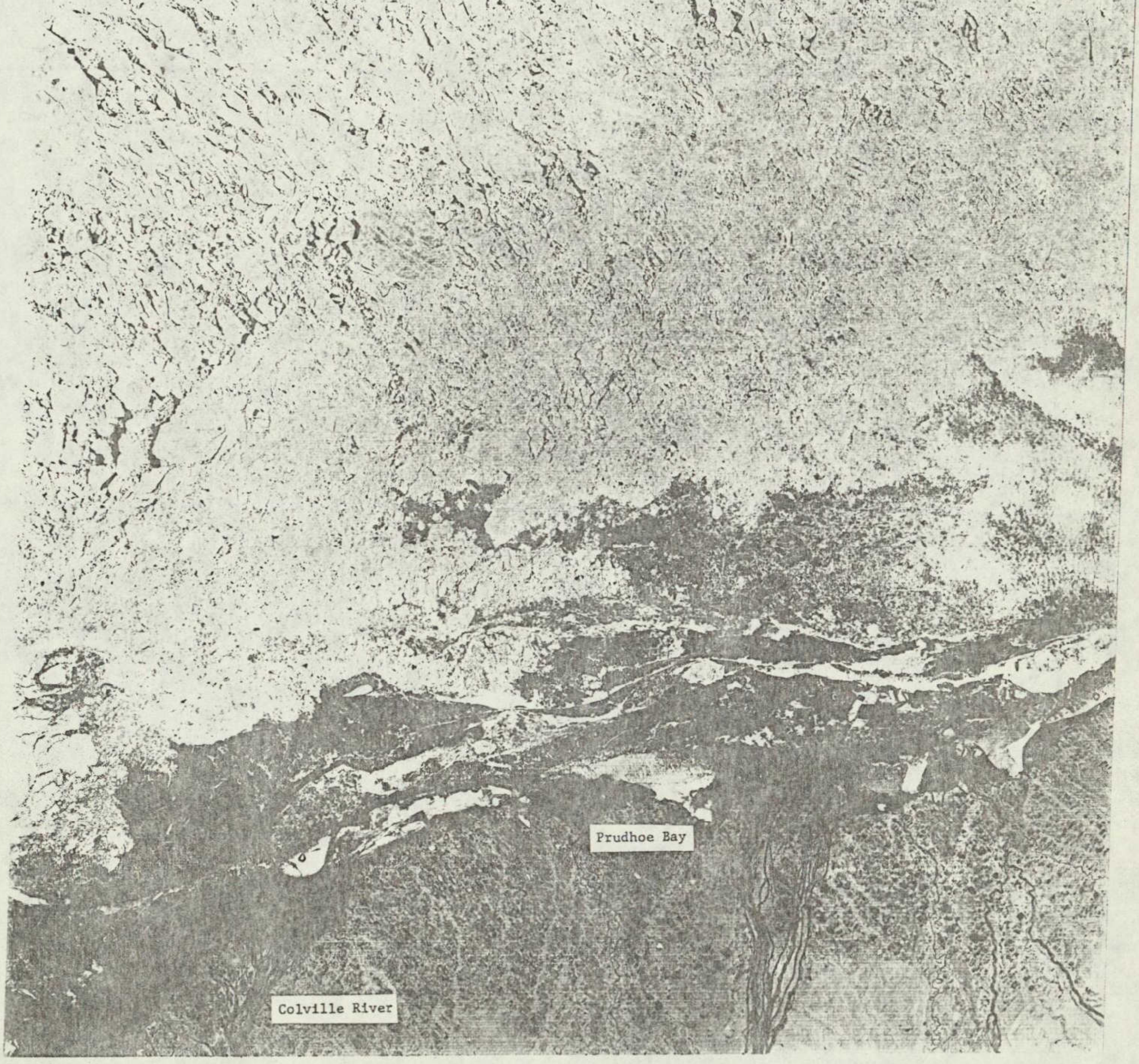

Figure 7: Landsat image 1721-21143 obtained 14 July,1974 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.

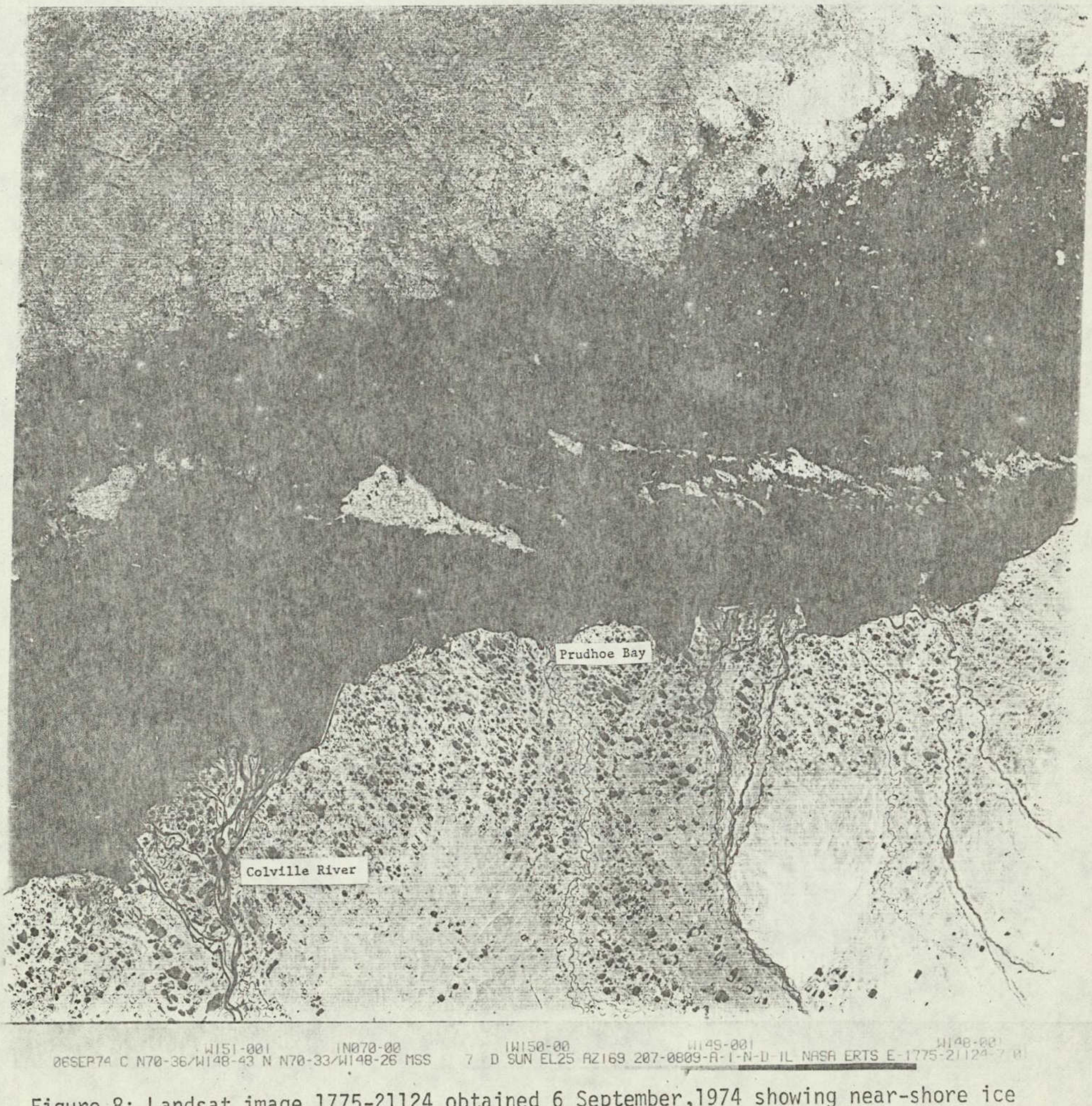

Figure 8: Landsat image 1775-21124 obtained 6 September,1974 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.

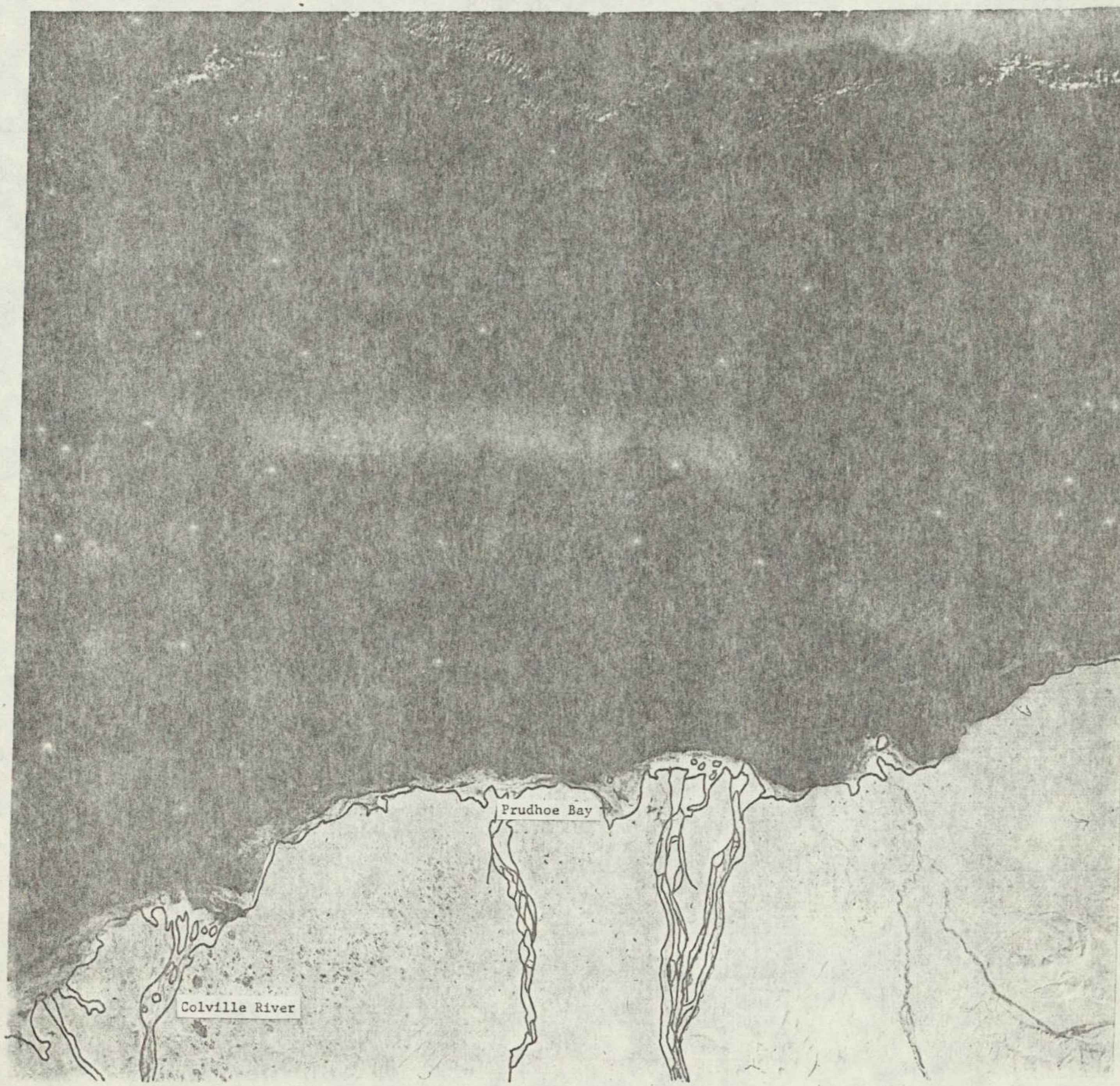

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Figure 9: Landsat image 1073-21223 obtained 4 October,1972 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.